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Final Technical Report
July 1997

STRATEGIC/TACTICAL OPTICAL DISK SYSTEM S/TODS AIRBORNE RECORDER

Lockheed Martin Communications Systems

Taras Kozak

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Rome Laboratory
Air Force Materiel Command
Rome, New York

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APPROVED: Fred N. Haritatos

FRED N. HARITATOS
Project Engineer

FOR THE COMMANDER:

JOSEPH CAMERA, Technical Director
Intelligence & Reconnaissance Directorate

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13. ABSTRACT *(Maximum 200 words)*

Rewritable optical disk technology affords the promise of larger storage capacity storage for many military applications. The original objective was to develop and deliver two advanced development model (ADM) optical disk storage systems for scientific and technical (S&T) reconnaissance aircraft and ground-based intelligence collection stations. The first ADM consisted of a single disk device capable of performing high-speed write, read and erase operations on a 14-inch diameter, rewritable optical disk. Each optical disk stores 12 gigabytes of user data. Key technical developments included the optical head assembly, optical disk media and high speed electronics design. The second ADM consisted of a fully automated optical disk jukebox storing 120 gigabytes. Key technical features include rugged, modular design for quick deployment set-up and tear-down, dual picker robotics for faster cycle time and an easily interchangeable disk cache for rapid data access in very large capacity applications. Both ADMS were designed, built and tested to comply with anticipated airborne and tactical environments.

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SECTION 1

INTRODUCTION

1.1 SUMMARY

This report describes the development of the Strategic/Tactical Optical Disk System (S/TODS) by Martin Marietta Communications Systems, Camden, NJ, for the Air Force Materiel Command's Rome Laboratory under contract number F30602–89–C–0008. The purpose of the program was to design, fabricate, test and deliver the S/TODS Advanced Development Model (ADM) Optical Disk system for use in Scientific and Technical (S & T) aircraft and Intelligence and Reconnaissance ground collection stations. S/TODS used the results of Durable I and Durable II (see RADC–TR–86–82 and RADC–TR–88–209, respectively) to conduct a Preliminary Design phase of the contract. The Preliminary Design identified key technical risk items and performed system trade–off studies and analysis. This provided the inputs for the Critical Design phase and eventual construction of the S/TODS ADM. In parallel to the Critical Design and fabrication, tests were performed to retire the major risks of the program and advance the program. At the end of these phases, the S/TODS ADM was designed, fabricated, integrated and field tested.

The program developed the highest performance, in terms of capacity and data rate, optical disk system to date for use in rugged military environments. Key developments in the S/TODS ADM include the optical head assembly, optical disk media and high speed electronics design.

The Optical Head Assembly contains important component developments such as the Focus/Track Actuator (FTA) and the dual laser write source module. Rewritable Optical Disk Media was developed and supplied by 3M Corporation. This media provides 12 GBytes of data capacity per disk. A high speed electronic architecture and associated electro–optic design provided for continuous write or read operation at data rates up to 25 Mbits/sec. In addition to the FTA important mechanisms that contributed to the compact rugged design include the loading mechanism, the disk spindle and the linear translation stage. The program culminated in a successful flight test demonstration under a wide range of conditions. The flight test, conducted on an RC–135 aircraft, demonstrated zero bit error performance under extremely stressful conditions. These conditions included tactical descents, mid–air refuelings, 60^0 bank turns, and both take–off and landing.

Key developments in the ADM include a further reduction in volume of the Optical Head Assembly (OHA) from the 125 cubic inches and five pounds of the Durable II design to two pounds and 27 cubic inches in the S/TODS design. This OHA includes a new design Focus/Track Actuator (FTA) developed for this program. The key technical risks retired in the head were the FTA and the write Laser Diode Array. A disk format was developed to allow recording 6 GB of data per side of a 14 inch Magneto–Optic (MO) disks. The disks were developed and delivered for the system. Key mechanisms developed include a compact disk loading mechanism to accommodate operation in a 19 inch rack, a disk spindle with vacuum chucking and a high performance ruggedized translation stage. Key electrical features include SCSI interface and the versatility and flexibility introduced by the use of field programmable gate arrays and standard 6U and 9U cards for the electronics.

1.2 SCOPE

This report describes the development of the Strategic/Tactical Optical Disk System (S/TODS). Included are its design requirements, tradeoffs, construction, tests, theory and performance.

1.3 BACKGROUND

The S/TODS is an Advanced Development Model (ADM) Optical Disk system designed for use in Scientific and Technical (S & T) aircraft and Intelligence and Reconnaissance ground collection stations. The S/TODS has demonstrated flight capability with tests on an RC–135 aircraft.

1.4 PROGRAM OVERVIEW

Design effort on the S/TODS system began in December, 1988. PDR occurred in Nov. 1989, DDU Hardware CDR in March 1991 and EU Hardware and all Software CDR in Dec. 1991. Media and DDU Hardware risk reduction associated testing began in March 1990 with tests of Laser Diode Arrays and continued into the early phases of system integration in August 1992. Tests of components, media and modules were conducted for design verification and parameter selection. This was particularly important in reference to the Media "preformat" where the dimensions and geometries do not lend themselves to accurate analysis

In the Preliminary Design phase, system architectures were established and allocated among subsystems. Interfaces were established electrically, mechanically, and optically. Preliminary layout of the DDU and EU were completed. Physical configuration was settled. Media design and construction was subcontracted. Specifications were prepared and vendors contacted for the micro–objective, translation stage and spindle.

In the Critical Design phase, the complete mechanical structure was detailed. The optics design was completed and fully ray traced. Individual boards were detailed and circuit design was established including the circuits contained in the FPGA's. Simulations were made of the digital circuitry. Subcontracts were let for the micro–objective, translation stage and spindle.

The Build and Test phase of the program began with the construction and test of individual boards and modules, mechanical, optical, electrical and software and ended with Integration and Test of the S/TODS.

Acceptance Test, Flight Test and Delivery represent the final phases of the contract. These will be followed by the integration of the S/TODS unit into an optical disk jukebox system (OJS) for further testing

1.5 GENERAL DESCRIPTION OF THE EQUIPMENT

1.5.1 General Performance Specifications

The specifications of the S/TODS equipment are summarized in Table 1.5.1–1.

Table 1.5.1–1 S/TODS Performance Specifications

SPECIFICATION	VALUE
System Interface	SCSI
Mounting	19 inch rack
Size	4.8 cu. ft.
Weight	165 lbs.
Power	120 VAC, 400 Hz, 20 A, single phase
Recording media	single 14 inch erasable disk
Disk Capacity	6.0 Gigabytes/side 2 sided disk
Data Transfer Rate (Burst)	> 40 Mb/s
Data Transfer Rate (Continuous)	0 to 25 Mb/s
Bit Error Rate (BER)	$< 1 \times 10^{-11}$
Disk Storage	in cartridge
Environment	modified Mil–E–5400

1.5.2 The S/TODS Equipment

The S/TODS Equipment is composed of the Electronics Unit (EU) and the Disk Drive Unit (DDU) and the interconnection cables. The test configuration also includes a Flight Test Computer (FTC), a Laptop Computer (used for control) and a VT220 (or equivalent) used for diagnostics. The equipment is shown in Fig. 1.5.2–1.

The EU front panel has only one control, the main power circuit breaker. The DDU front panel has pushbuttons for power, disk eject and test. Positive indication lights (red/green) show test result, and read and load statuses. Disks are loaded and unloaded through a door on the front of the DDU. All other functions except disk load and eject are initiated through the SCSI interface. Disk load and eject are initiated through the DDU by inserting the Media Assembly into the drive or by pressing the eject button.

1.5.2.1 S/TODS System Description

Functionally the S/TODS Optical Disk Drive is broken into the Disk Drive Unit (DDU) and the Electronics Unit (EU). Figure 1.5.2.1–1 is a block diagram of the S/TODS.

The EU is partitioned into four functional areas. These are the Interface and Control Electronics, the Data Formatting Electronics, the Write/Read Electronics and Servos and the Power Supplies. The Interface and Control area includes the SCSI Adapter which interfaces the external user port to the S/TODS and also the System Controller, which handles all high level internal command sequencing. The Data Formatting Electronics include the Write and Read Formatters, which add and extract the overhead to the data channels; the Track Buffer, which acts to buffer the rate differences between the Optical Disk Drive and the user port; and the Data Control Sequencer, which provides low level control and reference clocks. The Write/Read Electronics and Servos are comprised of the Laser Controller which establishes the laser levels and provides monitoring functions, the Read

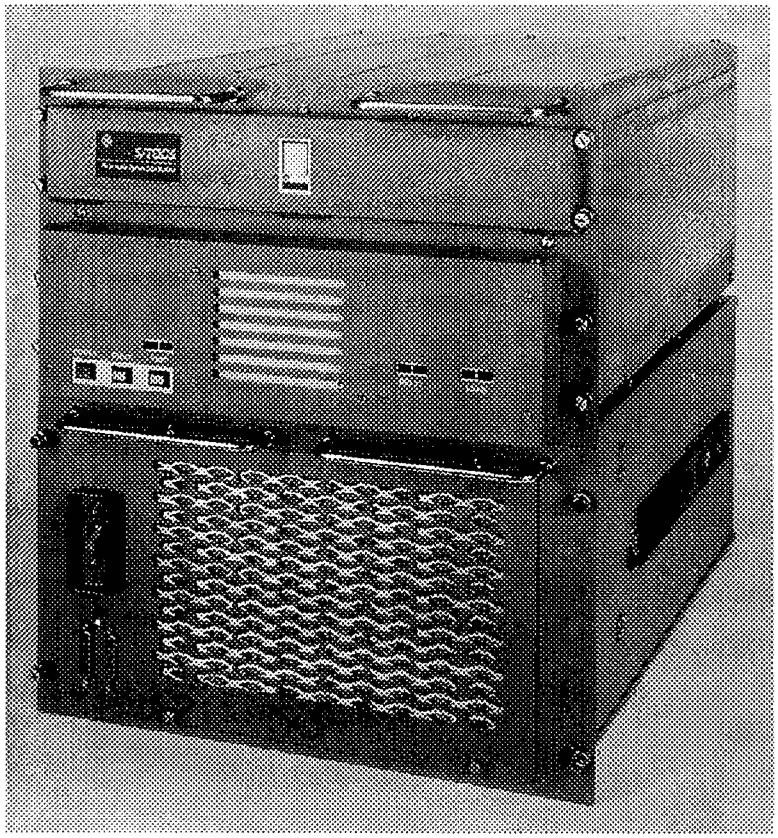


Fig. 1.5.2–1, S/TODS Equipment

Channel Processor which receives the raw signals from the disk and converts them back into digital form, the Focus/Track Servo and the Spindle and Stage Controllers.

1.5.2.2 Data Path Description

The S/TODS is a two track write/read unit with one data channel. The Data Formatting Electronics takes a continuous stream of user data from the SCSI port, manages the data flow, provides buffering and allocates the data to two parallel tracklets. Figure 1.5.2.2–1 shows the allocation of user data across the two tracklets. This division of data is totally transparent to the user. All realignment of the data in read mode is an internal function of the S/TODS.

The Read, Write and Erase operations may be better understood by reference to the System Block Diagram, Fig. 1.5.2.1–1.

For Write operations, data is loaded into the Track Buffer from the SCSI port after receiving the command block which is interpreted by the System Controller. The System Controller verifies that the disk is loaded, spun up and that the optics are in focus and the tracking servo locked. The Controller confirms that the proper location has been found on the disk for the write operation and permits data from the Track Buffers to be processed in the Write Formatters and sent to the Optical Head Electronics. The signals drive the Write Lasers which write the data onto the Disk via the Optics.

For Read operations, the desired tracks are accessed by the mechanisms under the supervision of the Controller. Data is read from the Disk using the Read Laser, the Read Detector and its Preamplifier. Signals from the Detectors are processed by the Read Channel Processor into digital form. The overhead is stripped from the data and the error correction is applied by the Read Formatters. Data from

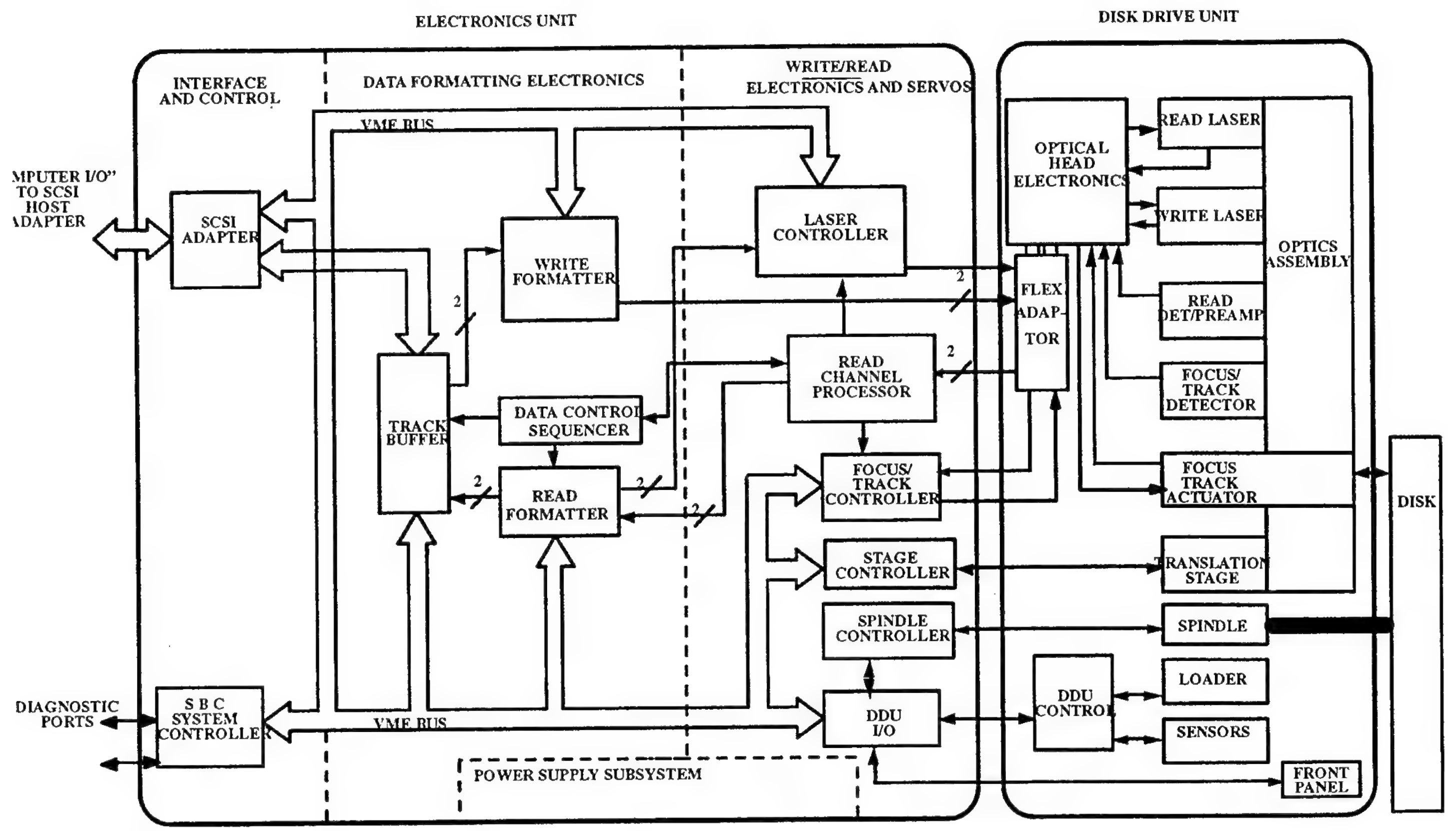


Fig. 1.5.2.1–1, S/TODS Block Diagram

the Read Formatters is loaded into the Track Buffer and made available to the user through the SCSI port.

For Erase operations, the desired tracks are accessed by the mechanisms as commanded by the System Controller. Then the Write lasers are driven to the required level for erasure and only the desired data areas are erased.

All the mechanisms necessary to load, unload, spin and access files on the disk are located in the DDU. In addition, some portion of the electronics are located in the DDU for control, support of mechanisms and to provide interface to the optical head electro–optics.

The DDU is partitioned into the optics assembly, and the DDU mechanisms, which include the spindle, translation stage and loader. The optics assembly contains the optics, lasers, and detectors necessary to write and read on the disk. It is mounted on the translation stage to access data on a spinning disk mounted on the spindle. Fine track access is accomplished by the FTA which is mounted on the optical head. The loader contains the motors and sensors that control the media assembly during load and eject operations.

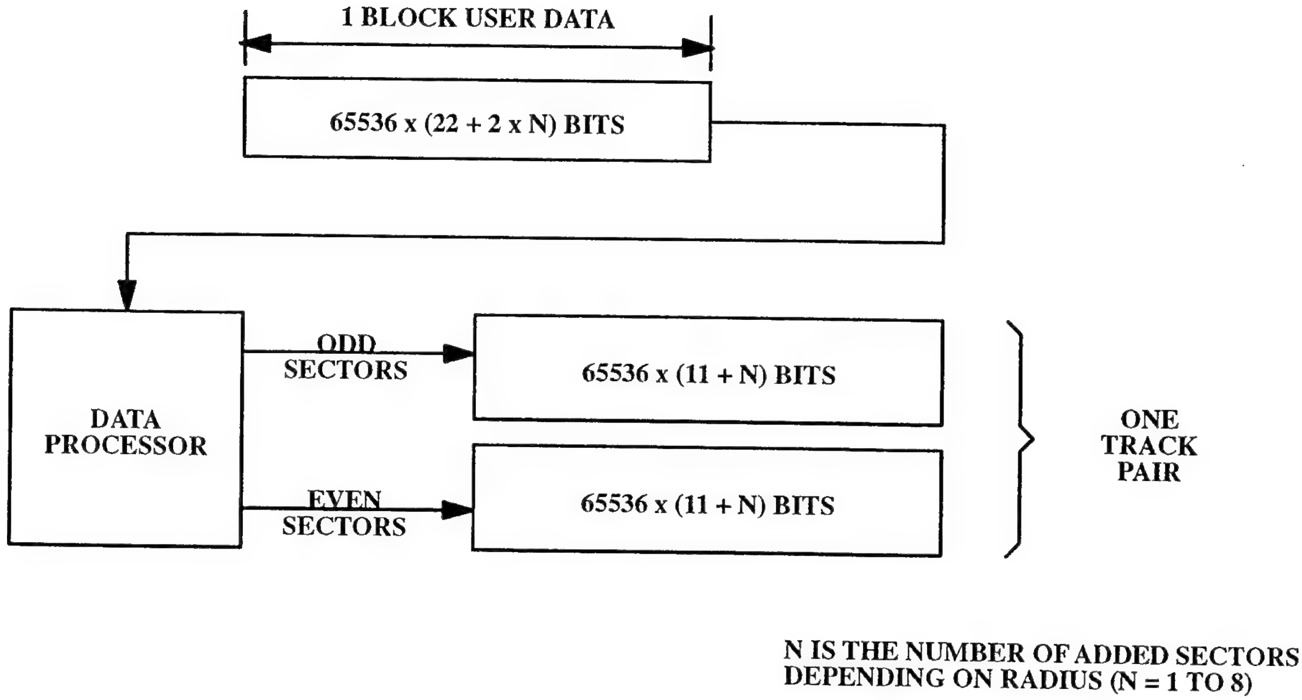


Fig. 1.5.2.2–1, User Data Allocation

1.5.2.3 Media

The S/TODS ADM uses a 14 inch Magneto–Optic erasable disk for write, read and erase. The Media is a double sided glass substrate disk produced under subcontract by 3M Corporation. Figure 1.5.2.3–1 is a photograph of a single disk in its carrier.

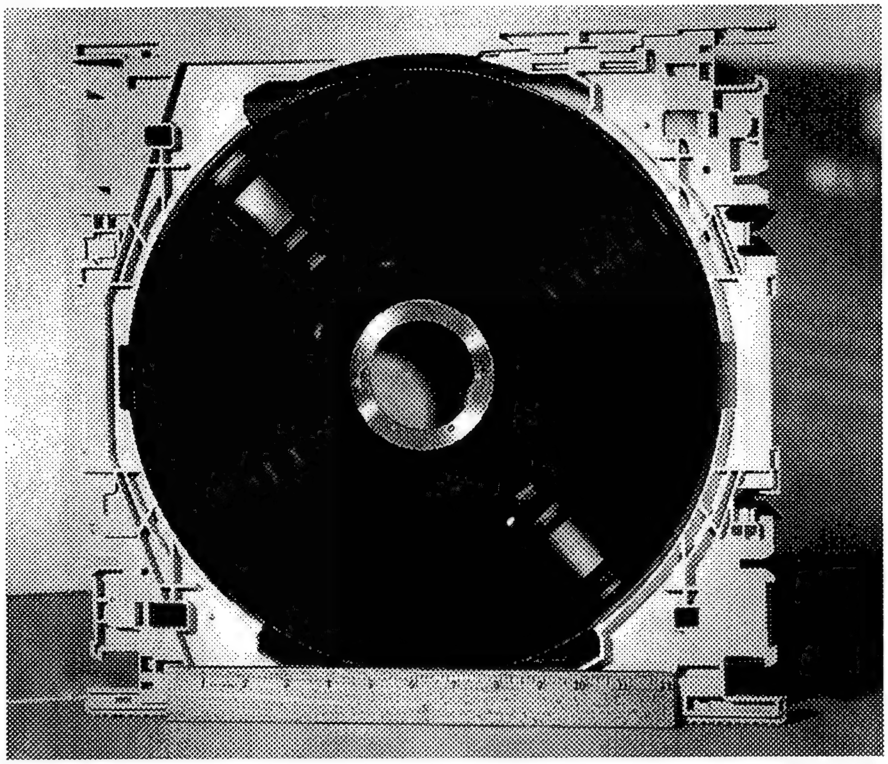


Fig. 1.5.2.3–1, Disk in Carrier

Table 1.5.2.3–1 is a listing of the performance specifications for this media.

Table 1.5.2.3–1 Media Specifications

Media Type	Thermo–Magneto–Optic
Substrate	Glass Sandwich
Dimensions	14.025 in. dia. <0.12 in. thick.
Mass	<500 gms.
Overcoat Thickness	1.213 +/–0.025 mm.
Magnetic Bias	225 To 300 Oe.
Write Power	6 To 12 mW @ S/TODS vel.
Write Power Threshold	> 4 mW @ S/TODS vel.
Read Power	2 mW max.
Narrowband SNR	> 45 dB @ 0.8 μm feature and 30 Khz. bandwidth
Raw Bit Error Rate	$< 5 \times 10^{-5}$
Preformat	ccw spiral groove
Spacing	3.2 +/– 0.1 μm
Coding	Custom
Environment	Modified MIL–E–5400

This media offers the following significant advantages over previous 14 inch M–O media:

1. Glass construction produces a thick dust defocusing layer increasing dust immunity.
2. Glass sandwich provides significant mechanical damping and enhanced ruggedness.
3. Metal hub area protects the glass and enhances handling
4. Format enhances data accesses and data integrity.
5. Media BER allows system BER of 10^{-11} to be achieved.
6. Write and Read powers are well balanced for laser requirements and playback needs.
7. Different readout modes for pilot track and data allows crosstalk rejection.

1.5.3 S/TODS ADM Performance

The S/TODS was interfaced to a flight test computer through the SCSI port. The system has operated without making bit errors through a flight test profile that include mid–air refuelings, 60 deg. bank turns, tactical descents and touch and go landings.. The Flight Test operates by transferring files of pseudo–random data and varying block length to the S/TODS from the Flight Test Computer, recording it and playing it back. The data is then transferred to the Flight Test Computer and checked bit–for–bit against the input data. At no time during several days of operation were any bit errors seen. This has demonstrated the expected capability of a ruggedized 14 inch M–O system.

1.5.3.1 Data Rate

The system operates at a continuous user data rate of 25 Mb/s. This is achieved over a full disk surface which has a capacity of 6 GB. Internal to the machine, each track is recorded at an effective raw rate of 16.7 Mb/s. Record power is about 8 mW at all locations on the disk. This is essentially constant because the BCAV operation of the machine. Making allowances for the system efficiencies, this requires about 2/3 of the nominal 30 mW power capability of the Laser Diode Array (LDA). This LDA structure is identical to single element lasers rated at 100 mW. On a pulsed basis, there is a large overpower capability in the LDA. This represents a substantially different case than that in the Durable EDM system which was rate limited by the laser power.

1.5.3.2 Capacity

The S/TODS system achieves 6 GB per side of 14 inch diameter glass based media. It uses closed loop tracking on a preformatted media to allow accurate placement of tracks. The format provides track number and start of track location information. This is used to allow the recording of single tracks. Each individual track writes sync, sector and EDAC information in conjunction with the data. The total overhead is 32.5 % over and above the user data.

1.5.3.3 Environmental Testing

The S/TODS demonstrated an enhanced operational range over commercial equipment. Disk operations were performed without bit errors over a temperature range of –20 through +40 deg C. ± 15g 1/2 sine wave shock was survived in all axes. 2g sine vibration from 5 Hz to 2 KHz was operated through with the exception of loss of track lock from 365 to 395 Hz, and loss of focus lock in the z axis only at 790 Hz.

SECTION 2

SYSTEM ANALYSIS

2.1 INTRODUCTION

System Analysis was performed for the S/TODS system. The design was based on the Statement of Work for Tactical Optical Disk Systems (TODS) PR NO. I–9–4266 dated 88 Dec. 27 and issues identified by Martin–Marietta during the initial phases of the preliminary design. This section summarizes the results of these studies. The System Analysis resulted in significant changes in the ADM design approach relative to the Durable EDM, primarily in the optical head and media design.

This system design is strongly driven by the expected capabilities of M–O optical disk media as extrapolated for 14 inch media. The basis for this media is results of 5.25 in. media produced for commercial products. The media parameters used to design the 14 in media and machine are the measured parameters of the 5.25 in. media. The media specifications are driven by ANSI / ISO Standards for 5.25 in. media and proposed 14 in. standards.

The MEDIA ASSEMBLY design started with criteria that it should defer to commercial practice. The cartridge assembly is the same as that employed in the Kodak 14" WORM drives. The Media and Drive have been designed to allow this direct application of commercial design. The principal properties of the cartridge are as follows:

Size	17.5 x 16.5 x 1.0 inches
Weight	4.5 lbs.

Components:
- Outer cover (caddy) removed for operation
- Locked spring loaded clamp (carrier) opened but not removed for operation

2.2 MEDIA

The Optical Disk Media for the S/TODS was developed and manufactured by 3M Corporation. The Final Report by 3M Corp. on the Optical Disc Media development program is included as Appendix B of this Report.

Data is stored on and retrieved from a 14" magneto–optic substrate incident glass disk. The disks are fabricated by first taking the glass substrate and replicating a grooved format onto the substrate. Then the M–O properties are added by depositing the recording layer onto the preformatted substrate. The recording layer is a transition metal – rate earth alloy sandwiched between protective dielectric films in a multilayer structure. Two glass disks are laminated together and an integral hub is added to provide double–sided media. The hub is required to stabilize the interface between the disk and the drive.

Critical specifications in addition to the system environmental requirements are:

Outer Diameter	14.025 +/ – 0.003 "
Inner Diameter	2.5 " taper
Clamp Zone	
Inner Radius	1.7 "
Outer Radius	2.7 "
Write/Read Zone	
Inner Radius	3.25 "
Outer Radius	6.8 "
Concentricity, Hub to Format	<50 μm
Mass Imbalance	<100 gm–cm
Axial Deflection	< 150 μm
Residual Focus Error (definition separate)	<0.25 μm
Mass	<1.5 lbs.
Thickness of glass	1.213 mm
Tilt of surface	<+/– 4 mrads.
Reflectivity	15 – 30 %
Reflectance variation (within disk)	+/– 10 % of average value of that disk
Magnetic bias field	225 to 300 Oersteds
Write Sensitivity	6 to 12 mW
Write power range (within disk for constant velocity)	< +/– 10 %
Read power	< 2 mW
Narrowband SNR (0.8 μm mark)	45 dB, 6.25 MHz tone, 30 kHz BW.
Raw BER	$< 5 \times 10^{-5}$
Pilot Track	3.25 to 6.8 "
Pilot Sense and Continuity	CCW viewed from recording side; ID to OD.
Pilot Track pitch	3.2 +/– 0.1 μm
Track Crossing signal	$0.20 < [(I_1 + I_2)_{max} - (I_1 + I_2)_{min}] / I_0 < 0.60$
Push Pull Signal	$0.40 < (I_1 - I_2) / I_0 < 0.65$

2.2.1 Recording and Playback

Recording and Playback from the S/TODS media combines Thermo Magneto Optic (TMO) Write, Erase and Read functions for the data with amplitude readout of optical phase encoded pilot track format information used for track address and track following functions.

2.2.1.1 Readout of the Pilot Groove

Readout of the Pilot Groove has special properties that are exploited to generate amplitude playback and a track error curve. First, if the groove is $\lambda/4$ deep and is adjusted in width to allow half the light to be reflected each from land and groove (1/4 from each side), a null is created in the reflected beam centered on the expected return path. Because much of the energy returns outside the aperture of the lens employed to focus on the groove, there is a large reduction in the signal as the spot passes over the groove. This amplitude modulation can be exploited for track readout. This effect is reduced as the groove depth decreases.

Second, if the groove depth is $\lambda/8$ and the spot is centered over one edge of the groove, the reflected beam is steered to one side. If it is center over the other side, the direction of the steering is reversed.

A significant portion of this signal is collected by the illuminating lens. By detecting the difference in intensity in the two halves of the collecting lens, a track error function is generated. Increasing the depth of the groove to $\lambda/4$ will reduce this modulation to zero.

Varying the groove depth and width allow the two signals, (the Track crossing and the Push–Pull signals), to be optimized relative to each other. Because of the difficulty of control, this is done experimentally. For S/TODS, this represents the preparation of a format disk. The format disk has the different bands in which the mastering power is varied causing a variation in groove width. Testing is used to pick the best parameters.

Readout of the pilot track is ideally accomplished by using the sum of the two polarization signals at the play detectors. In S/TODS, only one of the two signals is detected. This has not caused problems, but there is significant crosstalk from the data channel into the format channel.

2.2.1.2 Thermo Magneto Optic Recording and Playback

Data recording and playback from a Thermo Magneto Optic (TMO) media such as the disks used with the S/TODS system uses a thermal process for recording and erasing and a magneto optic process for reading the recorded data. The recording process uses heating by a small, focussed laser spot. The S/TODS read process uses a similar (or, for more conventional systems, the same at a reduced power) focussed spot of lesser power. A polarization rotation induced by the magneto–optic recording material is used to sense the magnetization of individual locations on the media.

The disks used in the S/TODS employ a magnetic material deposited in vacuum upon a glass substrate. Several layers are employed to allow the desired properties including lifetime, magneto–optic effect, sensitivity and a grooved preformat to expedite data access. Recording is made on the disk by orienting the remanent field in the recording layers. This recording is accomplished by heating the recording layer to the Curie temperature. At this temperature, the recording layer no longer has permanent magnetic orientation or remanent field. As it cools, the material becomes re–magnetized. Ordinarily, this orientation is random. In the presence of a bias field either from an external field or from adjacent areas of the disk, the domains of this cooling area will be oriented to neutralize the average field. In order to force a specific orientation, S/TODS employs a bias field during record and erase processes. This bias field is a minimum of 300 Gauss.

In recording on the media, the laser spot heats the media. The media responds by orienting the magnetic domains to neutralize the magnetic bias field. The area recorded is defined by a map of the region of the material that has been heated to or above the Curie temperature. S/TODS records on the media by first making an erase pass to orient all of the material in the recorded track. This is accomplished with the bias magnet providing a reversed magnetic field. To record, a second pass is made. The bias magnet is set in the normal direction. The laser is modulated to produce the desired magnetic pattern on the disk.

Playback from the disk uses the Kerr Magneto–Optic (MO) effect. When light strikes the disk surface of a magneto–optic material, its polarization vector is rotated around the direction of propagation. The direction of rotation is dependent upon the direction of the magnetization of the area on the disk (into or out of the disk). The rotation angle is less than 1 degree and is dependent upon the selection of the materials used for the disk, their thickness, their temperature and the wavelength of the light.

The detection technique is best understood by reference to Figs. 2.2.1.2–1 and 2.2.1.2–2.

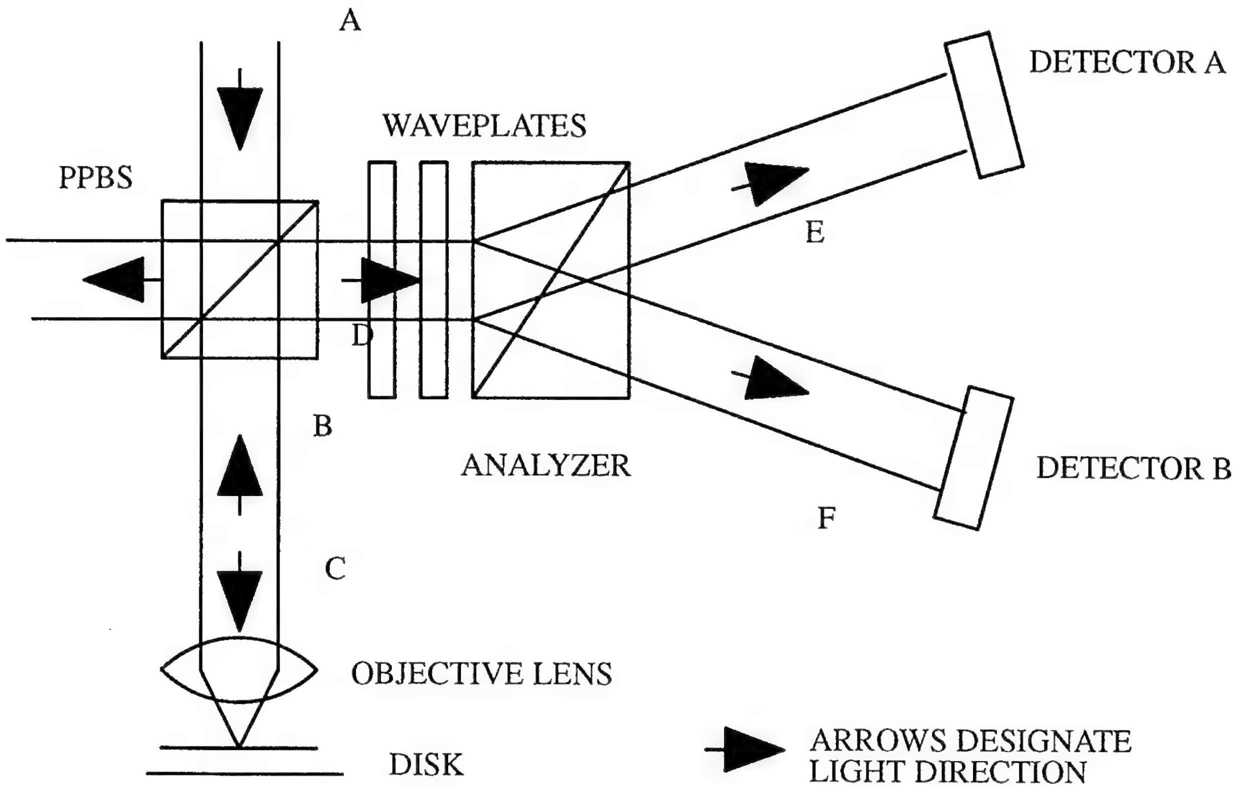


Fig. 2.2.1.2–1, Simplified Schematic of Playback System

Light from a laser enters the diagram from the top left (A). It passes through the Partially Polarizing Beam Splitter (PPBS). This PPBS has the property that light whose electric vector lies in the plane of the paper is transmitted with about 90 % efficiency. (This light is designated p–polarized; its electric vector plunges into the tilted surface. Light whose electric vector is perpendicular to the paper is designated s–polarized.) s–polarized light is 99+ % reflected at the same surface. In this case, the entering light is p–polarized and 10 % is waste. The light passing through is focussed on the MO surface. About 30 % of the light is reflected from the surface. This light has its polarization rotated by about 1/2 degree. The direction of rotation depends on the direction of the magnetization of the disk surface. To illustrate the detection process, follow the polarization for up and down states as the light passes from input to the system until it reaches the detector as shown in Fig. 2.2.1.2–2.

At A light is entering with its full amplitude and initial polarization. At B, light has been reduced in amplitude by passing through the PPBS, but its polarization is unchanged. At C, light has been reflected from the disk and its polarization has been rotated. The direction of rotation depends upon the magnetic state of the media. At D, the light has been reflected from the PPBS. The horizontal component has been reduced because its reflectance is only about 10 % for horizontally polarized light. The vertical component remains as high as before reflectance. (Its reflectance is 99+ %). This greatly increases the apparent angle of rotation. For this illustration, it is shown as being enhanced to 45 deg. The analyzer and wave plate combination then cause the light to switch from DET

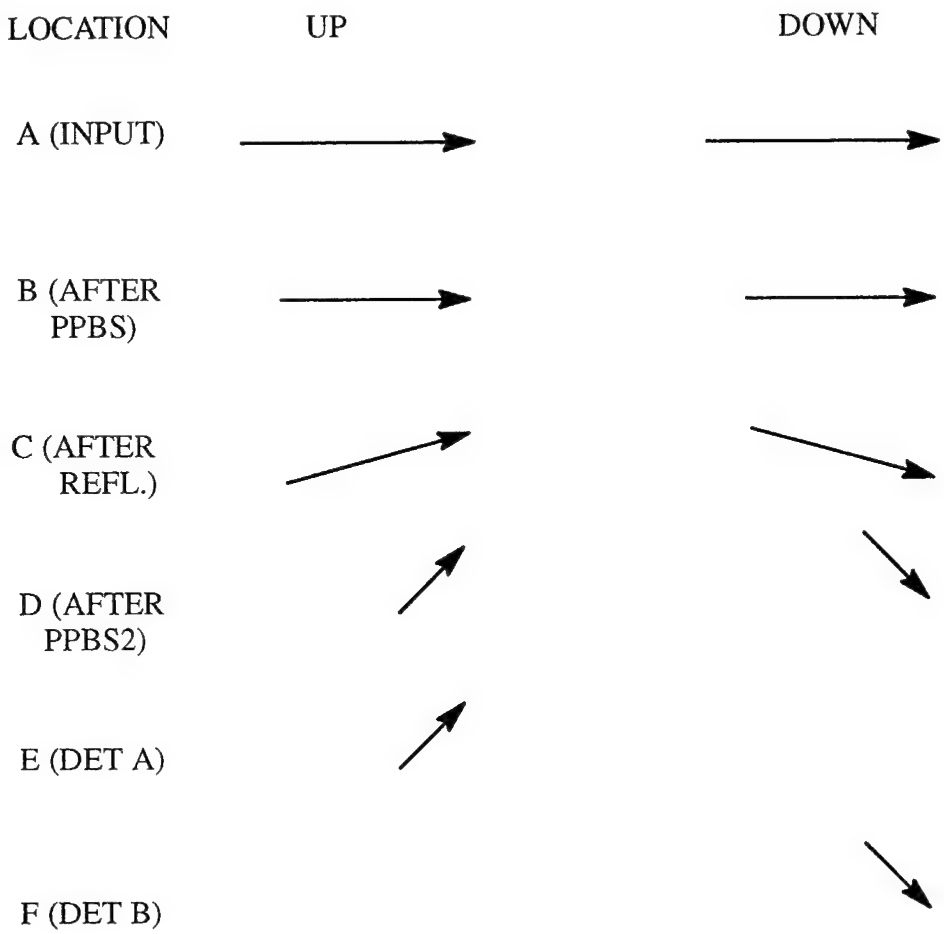


Fig. 2.2.1.2–2, Light Polarization in the MO Detection Process

A to DET B depending upon the magnetic state of the media. DET A to DET B are PIN silicon detectors with hybrid preamplifiers.

In the actual implementation, the rotation angles are only enhanced to about 5 deg. in the read path. The signal is processed by subtracting the signal from detector B from that from detector A. Signals that do not change with rotation are eliminated by subtraction. This leaves the detected signal as the sum of the signals at A & B. (A goes up when B goes down by an increment δ giving a signal $A - B = 2\delta$).

2.3 Data Recording

Data is recorded on the optical disk in two tracks. These tracks straddle a preformatted groove in the optical disk. Information designating the groove rotation number and angle are encoded in the preformat. Servos are used to follow the preformat and allow the information to be written to a designated location. The tracks are written by interrupting the laser while following the preformat. Because the edges of the written domains are localized and well defined they are used to record the data. The data is encoded using a Run–Length–Limited code according to a fixed format.

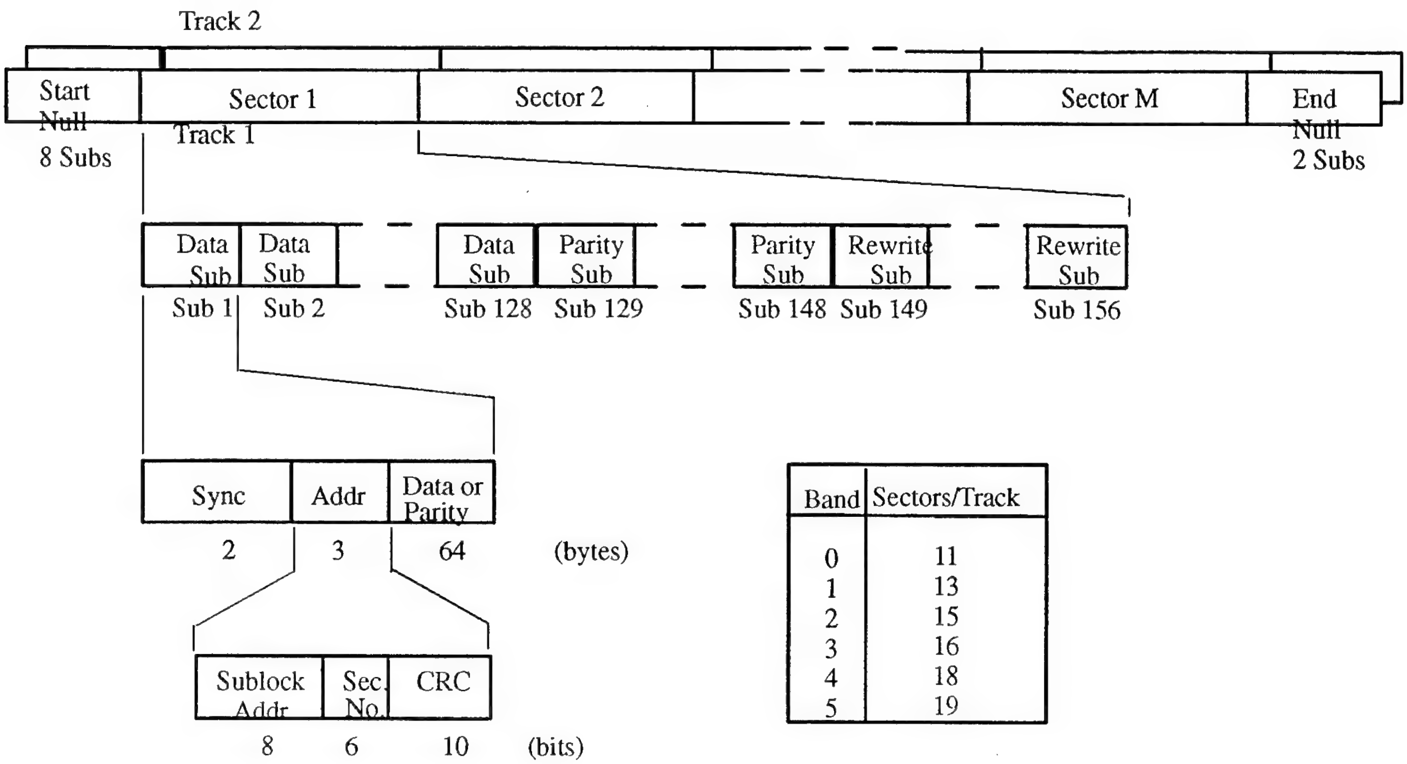
2.3.1 Data Format

The data format selected for the S/TODS is based upon studies of a limited family of formats that are particularly applicable to Optical Disk media. Sector and sub–block size were varied during the

studies in order to define feasible overheads. In order to meet the average data rate of 15 Mbps, the system design uses 2 tracks independently written at the same time. Segregation of the data into the two tracks is accomplished internal to the machine and is transparent to the user.

The selected architecture is designed for use with 14 in" erasable M–O media. The media was assumed to have a preformatted pilot track containing only track ID. The format support disk banding, rewrites and insertion of EDAC parity, sync and address information. Reading, writing and erasing is done on a track basis. Provisions are made for Phase Lock Loop (PLL) acquisition time at the beginning of a track and for spindle servo phase jitter at the end of a track. The format is also designed to support a form of bad sector mapping.

The data format for S/TODS is shown is Fig. 2.3.1–1 A data block consists of 16384 bytes and is



Band	Sectors/Track
0	11
1	13
2	15
3	16
4	18
5	19

Fig. 2.3.1–1, S/TODS Data Format.

shared between the two tracks. This is the smallest amount of data that can be accessed to and from the machine. The data block must be accessed by reference to a track number. Tracks on which a single data block are written are completed using fill data.

The data block size determines the organization of the buffers. (Other systems considerations such as the time to change spindle speed determine the buffer sizes.) Each track is formatted separately and consists of "m" data blocks or sectors and start and end nulls. Each sector includes 128 – 64 byte sub–blocks of data. Added overhead in each sub–block includes 2 bytes for sync, 8 bits for the Sublock Address, 6 bits for Sector Address and 10 bits for CRC checking of the addresses, 20 parity sub–blocks and 8 sub–blocks that are used for rewrite. Rewrites are confined to data written in a sector and cannot be used to support error suppression in other sectors.

The start null contains a high frequency pattern to allow the PLL to lock onto the track. This pattern occupies 8 sub–blocks or 4416 bits and allows 350 microseconds for clock lockup. The end null

of 1104 bits provides rate margin for the spindle of 88 microseconds. These nulls represent an overhead that varies with the number of sectors written per band. The overhead percentage contributed by these nulls varies from 0.76 % to 0.44 % depending upon the band.

Each sector contains 128 data sub–blocks, 20 parity sub–blocks and 8 rewrite sub–blocks. In this format, a sub–block is defined as the unit of data that is recorded between syncs. This also represents the minimum amount of data that can be rewritten. Each sub–block starts with 16 bits of sync and 24 bits of address. The address is made up of sub–block and sector addresses. It is protected by 10 bits of CRC. The CRC confirms address validity by detecting all errors of up to 4 bits.

The EDAC configuration provides a similar amount of data protection as the proposed ANSI standard for 130 mm Rewritable and WORM media. The validity of this choice has been analyzed and the results are presented in section 2.3.2 below. The EDAC is configured as a 10 error corrector and is implemented using the AHA 4010 ENDEC chip. Rewrites are handled on a sector basis. This makes the controller circuitry simpler but loses flexibility compared to earlier implementations handling rewrites on a track basis. The 10 error correction capability of the EDAC means that small defects do not have to be rewritten. There is sufficient reserve capacity in the EDAC when one or two errors occur in a sub–block as read by the RWW that the sub–block does not have to rewritten to maintain data integrity. The actual contribution of EDAC to overhead is 15.625 %. The actual contribution of rewrites to overhead is 6.25 %. In this format, overhead for sync and addresses is 7.81 %. Total overhead varies from 30.4 % to 30.13 %.

2.3.2 Overhead Tradeoff

Overhead percentage was calculated for 4 sector sizes (1, 2, 4 and 8 kbytes) and 3 sub–block sizes (32, 64,and 128 bytes). The proportion of data sub–blocks to parity and rewrite sub–blocks was held constant to ease the interpretation of results. All calculations are made for a track storing 851968 bits. The minimum radius at which this per track capacity is accommodated varies with the total amount of data stored on a track. It is a function of feature size and overhead on the disk. This leaves the essential tradeoff of user capacity versus overhead and drives the selection to lower overhead.

With a selection criteria of 35 % maximum overhead, the following combinations met the criteria:

With ID Sublocks	2 Kbyte sector–128 byte sub–block
	4 Kbyte sector– 64 byte sub–block
	128 byte sub–block
	8 Kbyte sector– 64 byte sub–block
	128 byte sub–block
Without ID Sublocks	1,2,4,8 Kbyte sector– 64 byte sub–block
	128 byte sub–block

Smaller sub–block size increases the overhead. This must be traded off against the resync interval and the possible loss of data due to loss of sync through a sub–block. A 64 byte sub–block does not cause a major impact in overhead. It is chosen for data integrity purposes.

2.3.3 Banding

The S/TODS has been designed to take advantage of the additional capacity, at a given minimum feature size, that can be added by adding sectors as additional track length is obtained as radius

grows. In S/TODS 6 bands are used employing from 11 to 19 sectors. The radii used vary from 91.78 mm to 171.84 mm. This enables a capacity of 6.06 GB to be attained relative to a maximum for this format in a Constant Linear Velocity (CLV) mode of 7.97 GB. Adding sectors whenever feasible would have increased this to 6.36 GB. The S/TODS disk format sacrifices some capacity in order to segregate the disk into 6 – 1.01 GB bands.

2.3.4 Pilot Track Format

Achieving the S/TODS performance goals requires a pre–grooved pilot track that includes track address information. This preformat is placed between the data tracks as shown in Fig. 2.3.4–1.

In order to permit packing both data tracks and the pilot track into a 3.2 µm space, advantage must be taken of the difference in readout modes for M–O and pilot track. This difference is used to suppress the crosstalk.

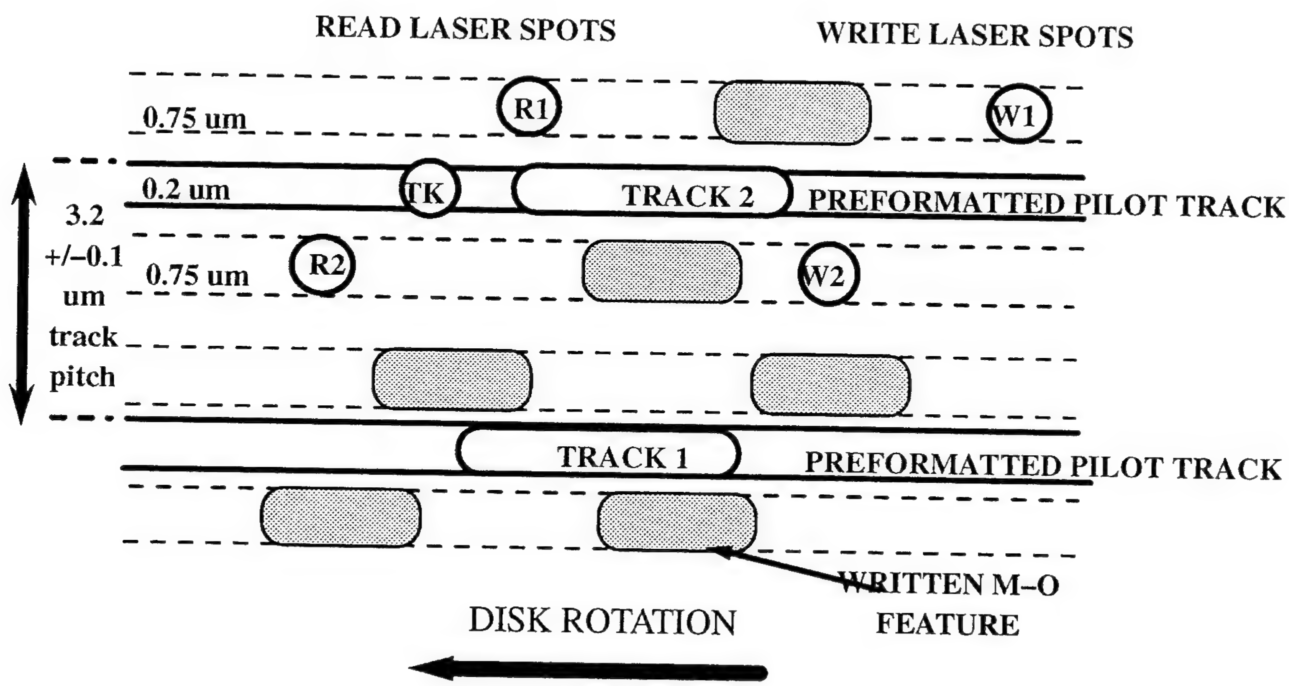


Fig. 2.3.4–1, S/TODS Pilot Track and Data Track Configuration.

2.3.5 EDAC Performance and the Error Model

The EDAC block size selected for the S/TODS is 128 bytes. 20 EDAC bytes are added to this block in order to allow correction of up to 10 bytes in error. In order to select this format, it was necessary to trade chip performance and block size versus the possible error rates of the media. The requirement is to achieve an end BER of less than 10^{-11}. The expected media performance is several times 10^{-5}. Operation in rugged environment could cause this to rise above 10^{-4}.

The S/TODS media error profile was unknown during the design phase of the contract. In order to model the system performance, random error rates varying from 1 x 10^{-3} to 1 x 10^{-5} were used. The assumption is valid if the width of the EDAC cube exceeds the length of any error bursts encountered. It remains valid if most of the errors occur in bursts. To assure this condition, large defects capable of producing longer bursts are mapped out using the Primary Defect List (PDL). No recording is done at these locations.

The probability of a number of occurrences (y) of an event (error) occurring in a number of trials (n), (the EDAC block length) is related to the probability of error in a single trial (p). Because these are byte oriented EDAC's, it is necessary to first calculate the probability of error in a byte and then in the EDAC block of n bytes. The probability for random errors is then:

$$P(y) = \frac{n!\, p^y (1-p)^{(n-y)}}{y!\,(n-y)!}$$

This was evaluated for block lengths of 64, 128 and 148 bytes, the latter being particularly applicable to a specific implementation. The results are summarized in Table. 2.3.5–1 where the byte error correcting capability required is shown for BER to be better than 10^{-11}.

Table 2.3.5–1 Required Correction Capability

Raw Bit Error Rate	1 x 10^{-5}			1 x 10^{-4}			1 x 10^{-3}		
Block length	64	128	148	64	128	148	64	128	148
Correction Capability Required (bytes)	4	4	4	5	7	7	10	13	14

In examining the results, it is apparent that for 64 byte block lengths, a 5 error correcting capability is sufficient up to BER's of 1 x 10^{-4}. It would leave little margin for the worst case operational scenario. With the availability of the AHA 4010 ten error correcting chip, selection of a block length of 148 bytes allows convenient data segregation and the ability to work at a BER exceeding 1 x 10^{-4}. Note that BER's approaching 1 x 10^{-3} quickly drive up capability requirements to an excessive degree. Use of a 64 byte EDAC block with a ten error corrector would require 31 % overhead just for the EDAC and would cause significant capacity loss.

2.3.6 Data Interleaving

Data from a number of EDAC blocks is interleaved in S/TODS as it is done in many other systems. This increases the burst error length that the system is capable of correcting. The size of the interleaving cube is coupled with the defect mapping (PDL) and the sublock rewrite strategy. This allows use of a larger proportion of the disk capacity while maintaining ample correction margin.

The interleave depth chosen for S/TODS is 64. This means that the size of the data block in the interleave corresponds to 1 sector on the disk. Theoretically, this would allow correction of a 640 byte burst without error. Of course, this also allows no probability of other errors.

Burst length error data is available for the same media formulation from ANSI document <u>Byte Error Rate Distribution on Media</u> by C. Mortenson of 3M, the manufacturer of the media. The maximum length of error burst observed with any regularity was 30 bits with 1.4 μm per bit. The size of the defect is thus roughly 40 μm in length. This corresponds to a maximum of 70 bits in error in the S/TODS system. With interleave 64, this can cause 2 byte errors in an EDAC word.

In the system, current operational values call for the system to PDL sectors that have error bursts over 32 bytes in length or that require more than 3 byte corrections in a single EDAC block. Data tested during disk certification includes EDAC and rewrite sublocks in order to provide full data security. This provides 7 bytes in all cases where rewrites have not been used that are available to correct error growth due to service stress or media performance degradation.

During actual data record operations, activity in the EDAC is monitored through the RWW. If more than 3 words are corrected in a single EDAC word, the sublock is rewritten. This verifies that the intended data margins are preserved in the actual data.

2.3.7 Synchronization Performance

In order to read the data and take advantage of the powerful error detecting code built into the S/TODS format, it is essential that the data be read into the proper locations in the playback files. At the input to the playback chain, this corresponds to correct placement in the EDAC cube. Data read while synchronism is lost cannot be recovered unless the EDAC has enough other properly read data to correct the bad data. The sub–block structure is designed to limit the number of bits lost after a loss of synchronism to a maximum of an additional 512 bits and an average of 256 bits. The strength of the synchronization technique comes from repeating the sequence every 512 bits. If synchronization is lost due to a media defect spanning one or more sublocks, data will be realigned upon detection of the next sync. This minimizes the data lost.

In analyzing the sync performance of the S/TODS format, the effect of random errors and defect areas on synchronization was considered. Neither is allowed to become the dominant factor in the BER. The following conditions were analyzed:

- 2.3.7.1 The effect of random errors
- 2.3.7.2 The effect of a defect in the start null area.
- 2.3.7.3 The effect of a defect area in the rewrite region.
- 2.3.7.4 The probability of losing sync with random errors.
- 2.3.7.5 The probability of false sync before acquisition with random errors.
- 2.3.7.6 The probability of false sync after acquisition with random errors.

The effectiveness of such analysis is dependent upon the randomness of the defects. Care must be taken in the design and integration to ensure that the sync integrity is not threatened by systematic problems such as intersymbol interference produced by such factors as errors in the write power.

<u>2.3.7.1 Random Errors</u>

The probability of being in sync at the start of data with random errors is assessed as follows. The start null is eight sublocks long. If the PLL takes two sublocks to acquire phase and frequency, six sublocks remain to acquire sync. Synchronism is declared after detecting an error free sync word

on two consecutive sublocks. Synchronism is declared lost when undetected for five successive sub–blocks. Attaining sync at the start of data will be achieved is sync is detected on two consecutive sub–blocks out of the next seven after PLL lockup. (Sync detection at the beginning of the first data sub–block also counts.) There are 128 (2^7) combinations of detecting or not detecting sync in these seven sub–blocks.

The combinations that would result in sync detection were evaluated along with the probability of a single sync being detected for BER's of 1×10^{-4} and 1×10^{-3} were used to calculate the probability of synchronism being achieved for the first data. The probabilities are 4×10^{-9} and 4.4×10^{-6}.

There are about 50000 tracks on a disk. At a BER of 1×10^{-4} it is extremely unlikely that the first data would ever be unsynchronized. At a BER of 1×10^{-3} the first data would be unsynchronized for roughly 1 track in every 250 disk sides. Later detection of sync can be used to recover the data through use of the EDAC if recovery occurs within the first few sub–blocks of data.

2.3.7.2 Start Null Defect

The effect of a defect in the start null area. A large defect in the start null that blocks the start null and even the first few sub–blocks of data will normally be PDL'd out. Sync will then be established in the remainder of the sector in preparation for a good sector by using the fill data written in the bad sector.

In the case where a defect is introduced after disk certification, it is possible to detect sync up to 10 sub–blocks into the sector without error. This will occur if the first ten sub–blocks are rewritten and the sub–block addresses are properly read for the rewrite sublocks. In addition, rewrites must not be needed to correct additional errors. Additional sub–blocks could be used if the EDAC is unloaded for further media defects.

2.3.7.3 Rewrite Area Defect

The effect of a defect area in the rewrite region. The object of rewriting sub–blocks is to replace sub–blocks with excessive errors with sublocks with fewer errors. In order to ensure that rewritten sub–blocks are always properly placed, sync and address fields must be error free before the rewritten sub–block is inserted into the data.

2.3.7.4 Lost Sync

The probability of losing sync with random errors. Synchronism is maintained by checking a 16 bit sync word leading every sub–block. To lose synchronism, at least one bit error must be made in 5 consecutive sync words. The probability of losing sync in the raw BER range of primary interest ranging up from 1×10^{-3} is acceptable. At 1×10^{-3} the probability of losing 5 consecutive syncs is 1×10^{-9}. At 5×10^{-4}, which is beginning to enter the range of BER's where the system can be expected to be fully operational, the probability of loss has dropped to 3×10^{-11}. This probability should not affect the data integrity.

2.3.7.5 False Sync Before Acquisition

The probability of false sync before acquisition with random errors and defect areas. Detecting a false sync word in data corrupted by random errors can be caused by two strategic bit errors affecting 4 possible combinations of 16 bits. At a raw BER of 1×10^{-3}, the probability of generating a false sync out of random data is $4 \times 10^{-6}/66536$ or 6.1×10^{-11}. Two consecutive false syncs square this probability, leaving an insignificant change of acquiring false sync out of random data. In a defect

area, there are 24 symbol positions each capable of being a one or a zero. To line up all 24 to generate a false sync, the probability is 1/224 = 6.0 x 10^{-8}. The requirement for detection of a second sync will minimize the impact of a false sync.

2.3.7.6 False Sync After Acquisition

The probability of false sync after acquisition with random errors and defect areas. After acquisition of sync by receiving two consecutive error free sync words, a window that spans the sync word plus a byte on each side of the sync word is set to reject any sync words that do not fall in the window. This reduces the probability of false sync by another 17:1. False sync can be achieved by random errors moving the location by one bit. For the chosen sync pattern, three properly located errors. At a BER of 10^{-3}, this gives a probability of false sync of 5 x 10^{-10}. This will cause the loss of 512 bits, giving a net contribution to the raw BER of 2.5 x 10^{-7}. This will not affect the raw BER. Note that spreading the EDAC through a cube allows the correction of several bad sublocks in a sector.

2.3.8 Format Conclusions

A robust format has been implemented in the S/TODS system. It is expected to provide ample system margin and an operating system BER of better than 1 x 10^{-11}. The system has been structured to exploit three levels of protection to the data:

1. Primary Defect List
2. Rewrite of poorly written sublocks
3. EDAC of great power

Along with the data integrity assured by this strategy, an equally strong strategy has been implemented to assure the proper data synchronization. The success of these strategies is born out in the system performance.

2.4 DISK DRIVE CONTROL

The S/TODS disk drive control path utilizes the SCSI interface according to ANSI Standard X3.131 (1986). This requires that the controller be resident within the unit. The interface standard encompasses such issues as:

Electrical specification of signal levels.
Timing relationships between signal lines.
Physical specification of cabling, connectors, etc.
Functional specifications of tasks the standard performs.
Command descriptor specification for the standard.

This standard was chosen to allow the integration of the drive into a broad spectrum of applications. It will allow nearly complete device transparency to system hardware and software. It lowers system overhead for disk control and allows higher data transfer rates.

The SCSI interface consists of a single cable that is daisy–chained to other SCSI units. It will accommodate not only disk drives but other peripherals. Up to 8 SCSI devices can be supported by a SCSI bus. The system can potentially be single initiator–single target, single initiator–multi–target or multi initiator–multi target. Specific features applicable to S/TODS include:

Higher level peripheral command set
Data rate up to 5 MB/s synchronous
Differential cables up to 25 m.
Command set that serves optical disk
Re–selection for better bus utilization.

A commercially available adapter module was chosen for the system. The use of a commercial grade device was selected for capability and cost purposes. This has resulted in a restriction of the temperature range. This can be corrected if the application requires by further development. The board chosen has a dual ported architecture. It allows SCSI access from the S/TODS via either the VME or VSB buses. This is important because the system is driven by the VSB access capability. The SCSI port is totally decoupled from the system; it functions as a fast First In First Out (FIFO) Random Access Memory (RAM). The board allows 30 MB/s internal data transfers over the VSB bus. It employs a 68020 on board processor to control its function.

2.5 MECHANICAL STUDIES

The packaging of the S/TODS is broken into three assemblies, the media, the DDU and the EU. The EU packaging is based upon the use of a standard 6U and 9U nest design. Power supplies and other support functions are also included. The MEDIA assembly is based upon application of a commercial design. It is primarily in the packaging of elements internal to the DDU that significant design study was conducted.

The DDU mechanisms are a direct descendent of the Durable mechanical assembly. The major necessary additions are the reduced packaging volume (17.75 inches wide, 24 inches deep, 10.5 inches high) and the Automated Loader Mechanism, needed for the loading and unloading the removable media onto the spindle. Principal areas of study, however, were in refining aspects of the Durable drive. Major areas were:

1. The vibration isolated deck assembly.
2. The spindle
3. The translation stage.
4. The optics assembly
5. The focus track actuator.

2.6 DECK ASSEMBLY

The Deck Assembly with the spindle, translation stage, disk, optics assembly and loader in place, comprises the most mechanically sensitive portion of the drive. Its configuration as designed for airborne service demands special consideration relative to its stability, particularly under shock and vibration conditions. Failure to comply with these special considerations may result in significant dynamic motion disturbances at the optical head – disk interface. Because of the size constraints of a 14 inch system, the S/TODS will be far more susceptible to these effects than 5 1/4 inch drives.

Salient features of an ideal ruggedized disk drive configuration include:

1. Mutual centers of gravity for deck, spindle and disk.

2. Mutual geometric centers for deck, spindle and disk.
3. Disk plane centered between the upper and lower spindle bearings
4. Isolation mounts, in a focalizing configuration, attach at or near the plane of the disk.

Mutual centers of gravity reduce the total moment arms for torque generation and the coupling of linear displacement to vibration modes. Note that the requirement for the single optical head impacts this and favors lightweight translation stage and optics. Mutual geometric centers were maintained in the drive to the extent feasible. Both this and the centering of the disk plane had to be violated to various degrees to allow for a practical and reliable means of loading the disk.

The deck structure is required to hold the deck, spindle, optics, translation stage and disk rigidly. In addition, the loader mechanism and related components are also mounted to the deck via a lightweight sheet metal support structure. This assures relative motion cannot occur between the media and the deck during a disk load operation. Finally, a low mass weight is required in order to meet the system weight requirements. A light metal, (Mg), casting was chosen to provide high stiffness, light weight and high vibration damping. This deck design is a direct descendent of the Durable design.

Vibration isolation in the S/TODS system is achieved by using coiled cable isolators. They are employed to limit the maximum transmitted shock to the deck to 7.0 G under test conditions and to rapidly attenuate frequencies above 50 Hz. Cable isolators were chosen primarily because of enhanced shock performance and stability of damping characteristics over the operating temperature range of the system.

2.7 SPINDLE DESIGN

The spindle is required to mount and rotate the disk at fixed rates from 10 Hz to 20 Hz. Minimal perturbation to the ideal constant rotational dynamics as reflected at the data surface of the disk media itself. This includes consideration of rotational speed variation, various aspects of spindle runout, both radial and axial, and a variety of other time variant mechanical effects. When coupled with the requirements for operation through Mil–E–5400 conditions, this represents a significant design challenge.

The requirements for the spindle are summarized below:

Size compatible with drive and chassis	goal 6.5 " Long x 5.5 " Dia.
Radial runout	
Recurring	<100 μin
Non–recurring	<40 μin
Axial runout	
Recurring	<120 μin
Non–recurring	<40 μin
Maximum torque	> 350 in–oz.
Properly interface centering device	
Properly interface chuck	
Weight	< 6.5 lbs. (goal)

Performance maintained over temperature $0 - 46\ ^{0}C$ (operating)
-57 to $74\ ^{0}C$ (non–operating)

(there are additional environmental and operational requirements)

The spindle bearing system is the single most important part of the spindle design. Ball or rolling element bearings were baselined for the system.

Runout is the most critical characteristic of ball bearings. First, there is "recurring runout". This is manifested by a "once around" radial or axial displacement of a rotating spindle system. Within limits, recurring runout is relatively easy to accommodate. It is constant and repeatable with respect to any given point on the disk recording surface. It may largely be eliminated by taking final machining passes on the spindle disk hub locating surfaces as the spindle operates under its own power. "Non–recurring" runout is a more difficult issue. It results from localized deflections of the spindle shaft caused by irregularities (high or low spots) on the balls or raceways of the bearings. Since the balls rotational speed is lower than that of the spindle itself, the non–recurring runout will counter rotate with respect to disk rotation. This produces a time variant displacement and mechanical disturbance to any given point on the disk data surface. This, in turn, may seriously interfere with the tracking and focus servo compromising overall system performance. The result of the S/TODS effort is a spindle with peak recurring runouts at the disk interface of less than 100 μi with non–recurring runout of less than 10 μi over the entire operating temperature range of the drive.

The precise performance of the spindle over the operating temperature range is achieved through the use of materials with similar thermal expansion coefficients (CTE). The spindle shaft and housing are machined from 440 stainless steel. This steel closely matches the CTE of the 52100 stainless of the ball bearings. The matching of CTE's reduces movement due to thermally induced stresses and maintains the bearing preload.

There are two significant changes to the S/TODS spindle bearing from the design employed in Durable II. 1. The disk plane is situated outside the bearing pairs (above the top bearing pair) to accommodate requirements of the loader design. This was implemented by increasing the load capacity of the upper bearing pair. 2. Differing bearing sizes are employed to reduce the potential for locked phasing of non–recurring runout in the two bearing pairs. Also, as a result of recommendations by the spindle vendor, Class 5 bearings are employed (Classes go as high as 9). The performance of the final articles substantiated this choice.

Major design features of the DC motor choice made for the S/TODS spindle reproduce the Durable II design. The design is a brushless DC motor employing 3 phases and Hall effect sensing. The configuration employs an outside rotor for high torque efficiency.

2.8 DISK CENTERING DEVICE

The purpose of the disk centering device is to repeatably radially locate the disk upon the spindle. The accuracy and repeatability of this location directly affects the performance of the system. Its accuracy must be traded off against the accuracy of the placement of the format on the disk and the tracking servo performance. The requirements may be summarized as follows:

Centering accuracy of system (includes disk format)	< 78 μm (.0031 in)
Lifetime	machine based

Reference	to side being read
Temperature range	0 to 40 ^{0}C
Axial Force	< 5 lbs.

Three concepts were traded off for the S/TODS spindle. All of them could be implemented with the S/TODS spindle and will reference from the side of the disk being used for recordings. They are:

1. Centering cone; ball bushing centering; spring loaded.
2. Centering cone; parallelogram springs
3. V–groove on disk; balls on spindle.

The centering cone with ball bushing is an industry common concept. It provides high radial stiffness with excellent longitudinal compliance. With good quality ball bearings and accurate cone and spindle construction it is capable of 100 μin runout capability. This allows much of the system tolerance to be allocated to the disk construction. It requires significant space in the spindle and is most easily implemented in a design where the disk is above the bearings. There is a possibility of a thermally induced interference causing seizure.

The centering cone with parallelogram springing is a concept that has been used at Martin–Marietta particularly for disks with large center holes. The ratio of compliance between radial and longitudinal motions is low compared to the first approach. This leads to a lowered centering accuracy. There is a possibility of a thermally induced interference causing seizure.

A V–groove on the disk could be used mating to spring loaded balls on the spindle. This technique has a high ratio of compliance and thus should be repeatable. This scheme has little accommodation to machining tolerances. Although it leads to fairly simple implementation and places no great burden on the hub, it is fairly easy to discard due to alignment requirement.

The centering cone with ball bushing was recommended for and employed by S/TODS. High centering accuracies were seen as expected. Thermal interference was eliminated by coefficient matching of the spindle, the cone and the disk hub.

2.9 DISK CLAMPING

In order for the system to function, the disk must be clamped to the spindle. Three general variations of technique were examined.

1. mechanical clamping
2. magnetic clamping
3. vacuum clamping

The basic requirements for the chucking technique are:

1. No slippage with 350 in. oz. torque
2. Can use area from 3.4–5.4 in. rad. (14 sq. in.)
3. Fast activation and deactivation (0.5 sec.)
4. Must accommodate g loadings

5. 60 lbs of clamping force to achieve rated torque and g loading performance
6. Operating temperature 0–40 ^{0}C.

The conclusions follow:
Mechanical clamping can be devised to operate with any desired spindle configuration. It can be activated in 0.5 sec. The mechanical clamp clamps on both sides of the disk. If designed with reference between the two halves, each part need generate only half the required force. If designed without reference between the two halves, the force to rotate the clamp must be transmitted through the disk.

Problems of the mechanical clamps include design and implementation, large head room, MTBCF unknown, increased inertia, and disk clamp conformance.

Magnetic chucking can be used without a head room penalty. The technique is used on commercial optical disk drives. It can be implemented either with permanent magnets or with electro–magnets.

A magnetic material must be added to the disk for the clamping to function. This will make referencing to the glass surface difficult. (A broad area reference is required in order to limit deformations.) If the magnetic material is used for reference , there is an additional tolerance build up for disk face runout and the force to rotate the disk must be transmitted through the hub. The magnet has to be large in order to generate the required 60 lbs of force and will increase the inertia of the rotating system increasing motor size. If a permanent magnet is used, disk removal either requires manipulation of the magnet to reduce the field or enough force to overcome the holding force. The mechanism required to reduce the field has a potential reliability impact while generating sufficient force to remove the media without reducing the field impacts the media design and reliability. The use of an electromagnet is made difficult by the force requirements, hence size, and the difficulties of power transmission.

Vacuum chucking can be adapted to the spindle configuration. It can be activated in less than 0.5 sec. There is no head room requirement. There are few high wear components. The inertia of the rotating system is not significantly affected. Uniform clamping is achieved when the disk is drawn into contact with the reference surface. This can also improve the disk surface flatness.

The vacuum system requires the design of the spindle with a vacuum transmitting (hollow) shaft and a rotary coupling. A high reliability vacuum pump, differential pressure sensor, and accumulator tank are also required. The accumulator tank can be mounted internally within the deck sheet metal structure. The volume required for the pump can be cleared in the bottom of the deck sheet metal and the pump can be mounted to the floor of the chassis. This mounting configuration isolates pump vibrations from the drive. The pump lowers the pressure of the accumulator tank to the preset vacuum level and turns off. When a disk is loaded onto the spindle, a solenoid valve opens connecting the accumulator tank to the spindle. As the differential pressure between the tank and the external environment changes beyond the preset range, the pump turns on and increases the differential pressure between the tank and external environment until the lower pressure level is reached. The pump then turns off and waits for the limit to be reached again. The cycle will continue until the power is turned off. The cycling of the pump, as described, extends the MTBF of the pump well beyond that of the drive. On balance for this application, the vacuum hold down system was chosen and implemented. Its operation has proven reliable and trouble free throughout the temperature and altitude ranges.

2.10 THE TRANSLATION STAGE

The S/TODS Linear Translation Stage System consists of a linear motion (electromechanical) motion stage assembly, and a physically separate (electronic) control subsystem. The environmental requirements for the stage add significant restraints. The LTSS provides coarse positioning of the optical head assembly along a radius of the disk shaped recording medium.. (Fine positioning is provided by a second actuator mounted on the LTSS but not part of the LTSS). The LTSS is requires to function in either of two basic operational modes:

1. The track seeking mode, in which the stage is required to move rapidly to position the optical head over the commanded data track.
2. The slew mode, in which the stage is required to move continuously such that the focussed spot coming from the optics onto the disk will be maintained within the acquisition limits of the fine–tracking actuator system.

From studies conducted during the Durable II contract, many of the configuration requirements had been determined. In particular these are:

1. Precision Ball lead screw drive.
2. Rotary DC Motor
3. Incremental encoder
4. Preloaded Crossed Roller Bearing

The S/TODS LTSS specification has the following major elements:

Size	8.5 x 3.9 x 2.4 inches; properly located 2.0" dia. x 5.00" long protrusion for motor
Weight	< 13 lbs. (10 goal)
Performance (with 3 lb dummy load):	
Range of travel	
maximum motion stroke	3.6 in.
Operational stroke range	3.2 in.
Acceleration	< 2 G
Time for 3.2 in. stroke	< 350 ms (goal 300)
Time for 20 μm stroke	< 40 ms
Parking accuracy	+/– 2.0 μm (+/– 0.5 μm goal)
Parking jitter	+/– 0.5 μm
Low speed slew rate	32.1 to 55.5 μm/s
Fiducial position	+/– 0.5 μm
Control electronics:	
Control bus	VME
Configuration	2 (max.) 9 U 160 mm Eurocards
Power source:	

Power supplies in EU	+5, +/– 15 V; one other for main drive.

As with the spindle, the translation stage used matching CTE's for the rollers, ways, lead screws and housing to maintain the performance over the operating temperature range. A low out gassing lubricant is used on the stage and spindle bearings to reduce the possibility of lubricant deposition onto the optics assemblies. ANDOX "C" was the chosen lubricant.

2.11 OPTICAL HEAD ASSEMBLY

The Optical Head Assembly for the S/TODS unit reproduces the functions of the Durable EDM. The system capacity is driven by the feature size at the disk. The DDU and LTSS size and weight are driven by the size of the OHA. Major design goals for the S/TODS unit reflect these criteria:

1. Upgrade the system to allow use of 0.8 µm min. features.
2. Reduce the overall envelope from in excess to 200 cu. in. to less than 20 cu. in.
3. Reduce the weight to less than 2 lbs.

In order to achieve these goals, redesign of individual modules within the OHA was emphasized to reduce complexity, increase integration of components into single packages and produce an OHA which would have its optics paths restricted to a single plane.

The major risk areas identified in the OHA were the Laser Diode Array (LDA), used for Write and Erase functions and the Focus Track Actuator (FTA). The risk associated with the LDA was abated by the availability of a commercial product before completion of the design. The risks associated with the FTA were reduced by design, construction and test of a new, high performance design before final system integration began.

Specific design requirements introduced to the S/TODS OHA are:

1. Redesign of the source modules to reduce size, eliminate temperature control by athermalization of the module and achromatize collection optics.
2. Redesign of the relay optics to reduce their size and overall path length.
3. Respecify the Partially Polarizing Beam Splitter to nominal system requirements at 45 deg. incidence.
4. Incorporate achromatization in the Beam Expander.
5. Use a hybrid PIN detector/preamp for the Play Detector
6. Use a custom double bi–cell detector for the Focus Detector.
7. Use of polarization shifting by the introduction of half wave plates to allow planarization of the optics.
8. Incorporation of a custom micro–objective and FTA for increased optical and mechanical performance.

The result of the redesign of the OHA assembly is shown in figure 2.11–1. The optical componants are illustrated in this simplified layout at approximately 1:1 scale. The view is from the side.

2.11.1 FOCUS TRACK ACTUATOR

A Focus Track Actuator was developed for the S/TODS. This development was prompted by the inadequacies of previous designs. Previous designs included a commercial FTA from Olympus.

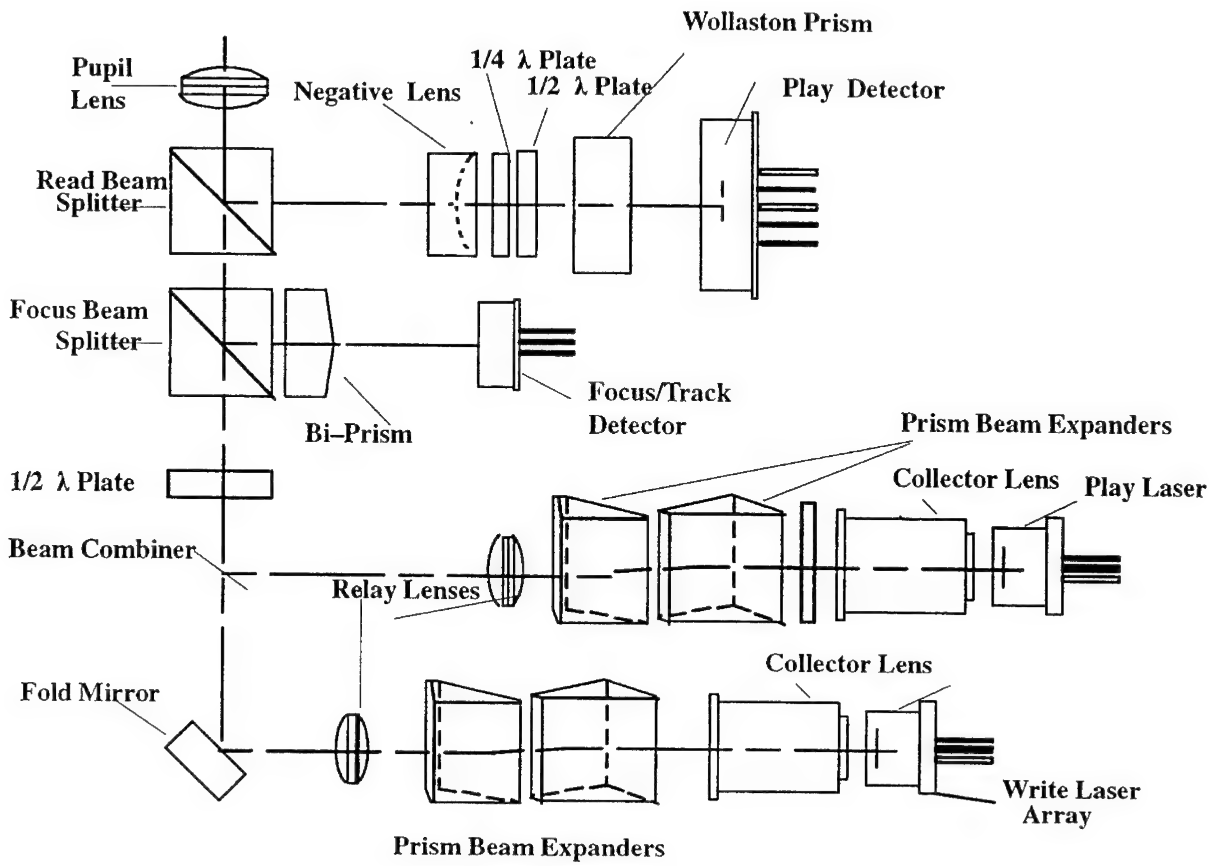


Fig. 2.11–1, Optical Head Assembly Schematic.

Although this represented high performance, there were significant shortcomings. The lens in the FTA had inadequate field flatness, working distance and Numerical Aperture (NA) for the S/TODS system. The second possible design was an FTA designed for the SODR program. That FTA had significant shortcomings in travel and in resonances.

After careful analysis of the previous designs, it was determined that S/TODS would employ a new FTA design. The major requirements are:

Volume	< 1.5 cubic inch
Weight	few ounces
Lens mass	about 3 gms.
Travel (static)	
Focus	+/– 0.25 mm
Tracking	+/– 0.075 mm
Optics centerline to edge of housing	< 18 mm
Minimum system bandwidth	2.5 kHz
Fundamental resonance frequency	about 100 Hz
First structural resonance	> 10 kHz (goal 12 kHz)
Shock survivability	7 g all axes
Tracking displacement sensor	

Accuracy	1 µm
Range	+/– 0.075 mm

Details of the design are given in Section 3.3.1.8, results of testing are given in Section 3.3.1.8.2.

2.12 PACKAGING AND ENVIRONMENTAL CONTROL

The disk drive unit employs forced ambient air cooling. A high efficiency 150µm Pore size filter is used to filter the cooling air. The filter must be changed on an as needed basis dependent on the environment. The filter is easily visible and accessible from the front of the drive. An internal temperature sensor is used to turn on the cooling fan when the laser temperature exceeds a preset limit. (The laser is the temperature sensitive component of the drive.) The fan will run continuously until the lower temperature limit is reached. If the temperature exceeds the max limit of 40^0C , the red ready light will illuminate and laser operation will cease until the temperature drops to within the operating range. The fan will also run whenever the mail slot of the drive is open. This assures air flow from the mail slot to eliminate contamination from entering the drive.

The disk drive unit employs the use of an RH sensor. The RH sensor monitors the humidity and the temperature of the air inside of the drive. If conditions are correct for condensation to form, the red ready light will show and the lasers will cease operation. The fan will continue to run changing the air inside the drive i.e., (temperature and moisture content) until the possibility of condensation is not present. The green ready light will then show and the lasers will continue operation.

The disk drive unit employs foil heaters mounted behind the optical head. When the laser temperature sensor reaches a preset low limit, the heaters will turn on assuring proper laser and optical operation. Because the entire disk drive unit employs similar CTE's for all non correctable interfaces, only the optics need to be heated to assure proper drive operation to -20^0C.

The temperature and humidity range of the drive can be improved by using a remote environmental control unit. The remote unit attaches to the current drive through two flexible ducts exiting the rear of the DDU chassis. The air will be continuously cycled from the drive through the control unit to warm, cool, or dehumidify as needed. The environmental control unit will occupy 10.5 inches of 19 inch rack height. It extends the operating temperature range from -40^0C to $+50^0$C. It also allows for continuous operation without condensation fears. The current drive is designed to accept the remote environmental control unit.

2.13 ELECTRONICS UNIT

System studies for the Electronic Unit were concentrated in the packaging and component selection areas. The EU was designed without environmental control, subjecting all of the components to the full range of environmental exposure. Primary design requirements for the EU are:

Size	2.1 cu. ft.
Mounting	19 inch rack
Estimated weight	67 lbs
Power input	120 V ac, 400Hz
Voltages	+5, +&–15, +48, +28 volts DC
Modules	

6U	3
9U	14
Computer Interface	SCSI
Corrected BER	1×10^{-11}
Data Rate	25 Mb/s (continuous)
Temperatures	
operating	–40 to + 46 ^{0}C
non–operating	–57 to +77 ^{0}C
Environmental	Mil–E–5400

Physical compaction of the EU is achieved through the use of LSI technologies. The 3 phase encoder / decoder (ENDEC) is a Martin–Marietta designed CMOS gate array. The Reed Solomon EDAC and the VME and VSB are all vendor supplied custom LSI. Control and Format functions were allocated to field programmable devices. These devices are high density, general purpose logic arrays. The configurations for the field programmable devices are PROM loaded at power up. Configurations are alterable by reprogramming. Available features for a Xilinx XC3090 include:

9000 equivalent gates
320 configurable logic blocks
928 Available flip–flops or latches
50 MHz toggle rates
144 User I/O's
PGA or PLCC package
Mil version available
Full development support

This type of capability permits drastic reduction in size without the commitment to design of ASIC's for the drive. This is important in an ADM where design alteration to accommodate unforeseen problems could require the redesign of ASIC's.

SECTION 3

S/TODS DESIGN

3.1 INTRODUCTION

This section describes the design of the S/TODS ADM unit. It is described first on a system level. Next, details of specific subsystems are given.

3.2 SYSTEM DESCRIPTION

Functionally the S/TODS Optical Disk Drive is broken into the Disk Drive Unit (DDU) and the Electronics Unit (EU). Figure 3.2–1 is a block diagram of the S/TODS.

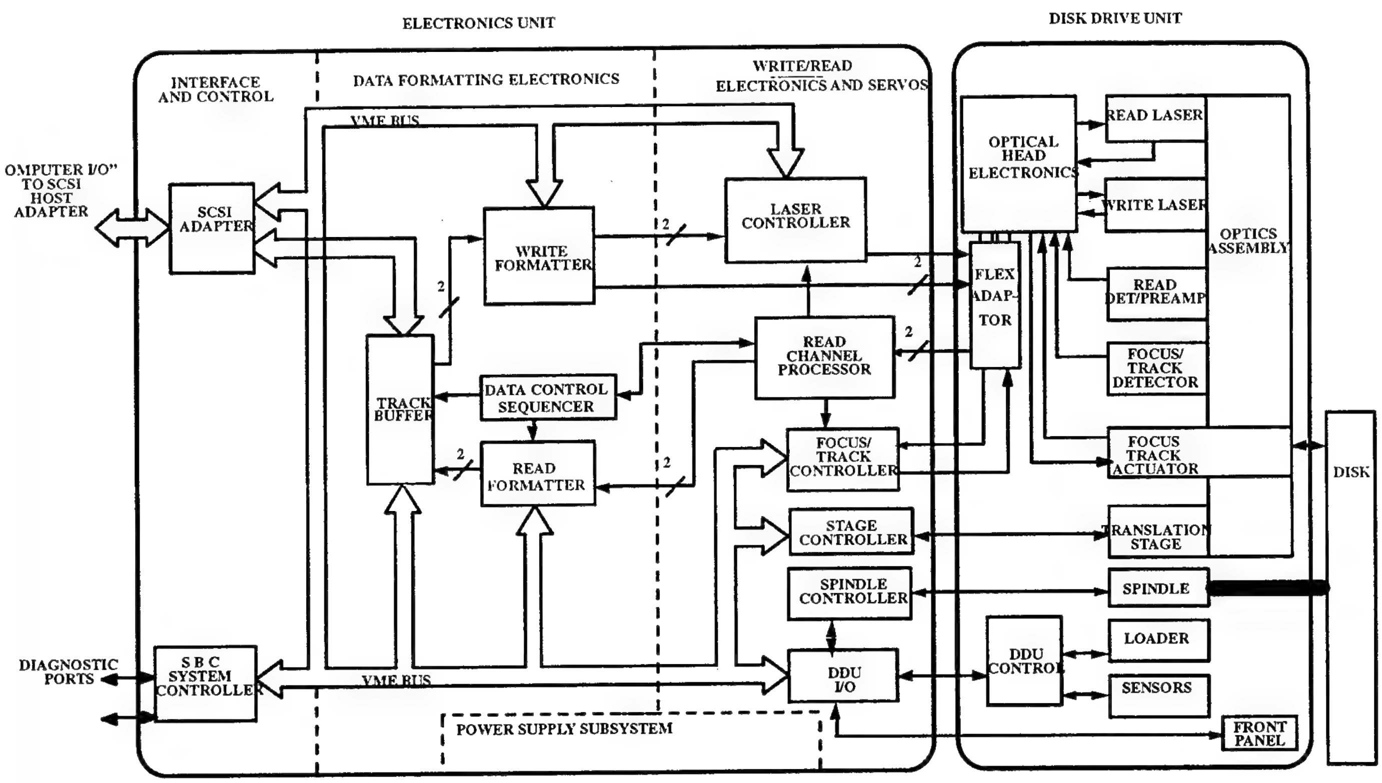


Fig. 3.2–1, S/TODS Block Diagram

All the mechanisms necessary to load, unload, spin and access files on the disk are located in the DDU. In addition, some portion of the electronics are located in the DDU for control, support of mechanisms and to provide interface to the optical head electro–optics.

The DDU is partitioned into the optics assembly, and the DDU mechanisms, which include the spindle, translation stage and loader. The optics assembly contains the optics, lasers, and detectors

necessary to write and read on the disk. It is mounted on the translation stage to access data on a spinning disk mounted on the spindle. Fine track access is accomplished by the FTA which is mounted on the optical head. The loader contains the motors and sensors that control the disk during load and eject operations.

The EU is partitioned into four functional areas. These are the Write/Read Electronics and Servos, the Data Formatting Electronics, the Power Supplies and the Interface and Control Electronics. The Write/Read Electronics and Servos are comprised of the Laser Controller which establishes the laser levels and provides monitoring functions, the Read Channel Processor which receives the raw signals from the disk and converts them back into digital form, the Focus/Track Servo and the Spindle and Stage Controllers. The Data Formatting Electronics include the Write and Read Formatters, which add and delete the overhead to the data channels; the Track Buffer, which acts to buffer the rate differences between the Optical Disk Drive and the user port; and the Data Control Sequencer, which provides low level control and reference clocks. The Interface and Control area includes the SCSI Adapter which interfaces the external user port to the S/TODS and also the System Controller, which handles all high level internal command sequencing.

For Write operations, data is loaded into the Track Buffer from the SCSI port after receiving the command block which is interpreted by the System Controller. The System Controller verifies that the disk is loaded, spun up and that the optics are in focus and the tracking servo locked. The Controller confirms that the proper location has been found on the disk for the write operation and permits data from the Track Buffers to be processed in the Write Formatters and sent to the Optical Head Electronics. The signals drive the Write Lasers which write the data onto the the Disk via the Optics.

For Read operations, the desired tracks are accessed by the mechanisms under the supervision of the Controller. Data is read from the Disk using the Read Laser, the Read Detector and its Preamp. Signals from the Detectors are processed by the Read Channel Processor into digital form. The overhead is stripped from the data and the error correction is applied by the Read Formatters. Data from the Read Formatters is loaded into the Track Buffer and made available to the user through the SCSI port.

For Erase operations, the desired tracks are accessed by the mechanisms as commanded by the System Controller. Erasures are done for integer multiples of tracks. Track addresses are confirmed from the format track. After confirmation of the proper track mark, the Write lasers are driven to the required level for erasure. Erasure end upon confirmation of the appropriate end mark. This ensures that only the desired data areas are erased.

3.3 DISK DRIVE UNIT

The Disk Drive Unit, shown with adjacent Media Cartridge in Figure 3.3–1, contains the optics, electronics, and mechanisms necessary to provide read, write and erase operations on the optical disk media.

3.3.1 Optics Assembly

The Optics Assembly, shown in Figure 3.3.1–1, is an integral unit measuring 3.5" x 4.5" x 1.7" (external dimensions). The Optical Head Assembly (OHA) contains the laser sources, optics, and detectors that are necessary to perform write, read, and erase functions. The FTA, mounted on the

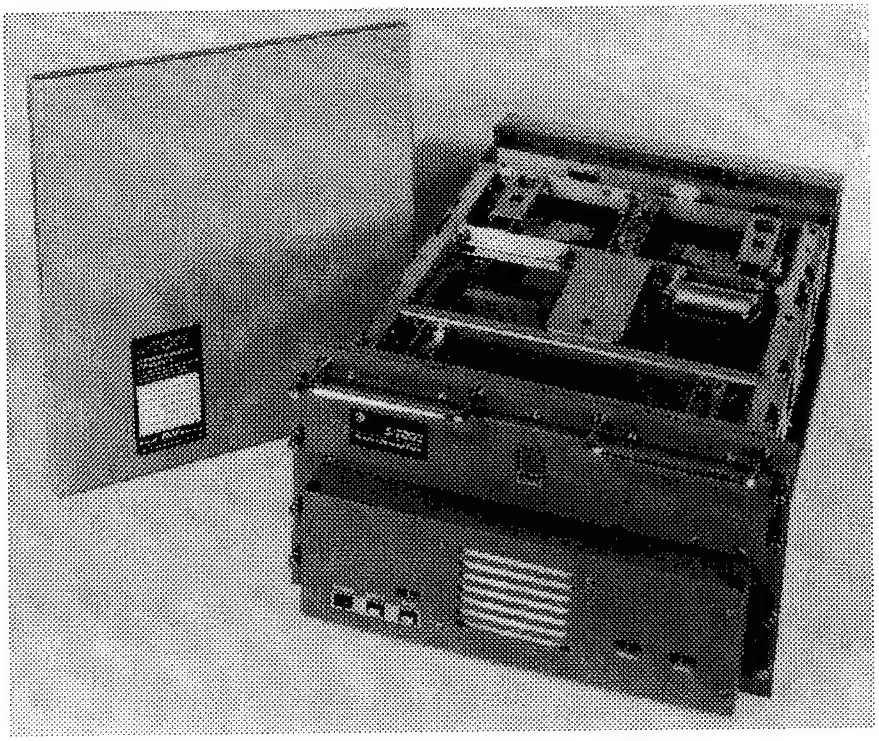


Fig. 3.3–1, Disk Drive Unit with Media Cartridge

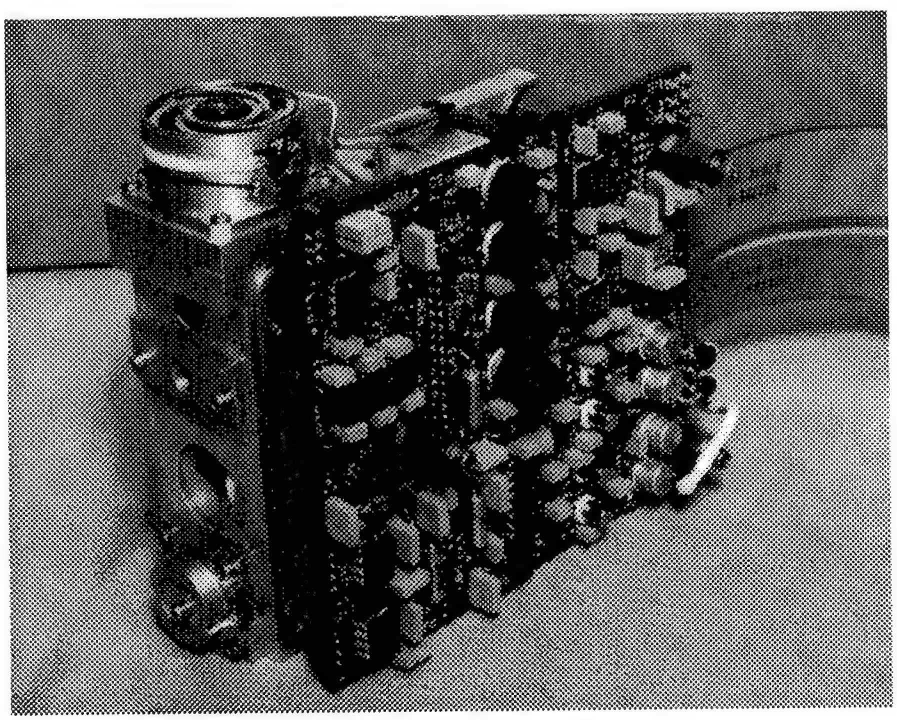


Figure 3.3.1.–1, S/TODS Optics Assembly

OHA, controls the final position of the write/read spots on the disk. The Optical Head Electronics provides the interface and control circuitry for the Optics Assembly.

The optical interaction with the disk for all functions is accomplished by focussing laser spots upon the disk. The geometrical creation and placement of those spots is a shared responsibility of the

OHA, the Media, the LTSS and the Spindle. The OHA creates spots with a fixed geometrical relationship at the focal plane of the Micro–objective. The Spot Format is shown in Figure 3.3.1–2.

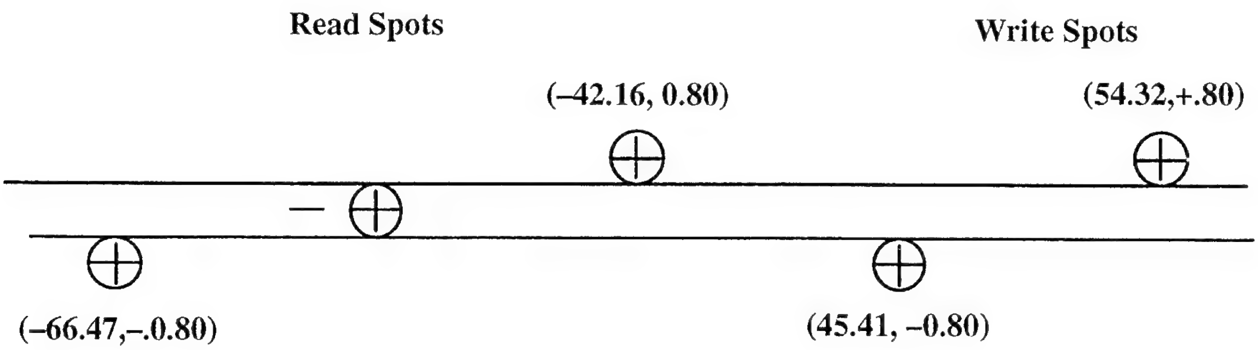


Fig. 3.3.1–2, Spot Format

The dimensions in parentheses are the distance along track and the distance cross track from the optical centerline of the micro–objective lens at the focal plane.

As can be seen in the diagram, the spots straddle the format track ("groove") on the disk. The total length of the array of optical spots is 111 µm. The separation of read and write spot groups is only 87 µm. The separation from the centerline of the groove to either play spot is 0.80 µm. The separation from the centerline of the groove to either write spot is 0.80 µm. The tracking spot is centered on the groove. By keeping the size of the group restricted, it was feasible to design a micro–objective with flat field to handle the group. This does have implications in the design of the beam combining optics. The mirror used for combining must have high quality near its edge over the diameter of each of the beams.

The S/TODS OHA components are shown schematically in Figure 3.3.1–3.

From the bottom of the diagram, there are four rows of components; the write laser assembly, the read laser assembly, the focus track sense path and the data detection path. The mounts for all the assemblies have requisite adjustment provisions and have been shown to be stable through environmental temperature, shock, and vibration testing.

In the Write Laser Assembly, light from the write laser is collimated by the the collector lens. The prism pair expands the write beams in one dimension to produce a circular beam. This is necessary because the laser sources emit an elliptical beam with roughly a 3:1 aspect ratio. The doublet relay lens forms an image near the beam combining mirror which lies at the end of the read laser path. A mirror at the end of the write laser path sends the write light to the FTA.

In the Read Laser Assembly, light from the read laser is collimated by the the collector lens. A grating is then used to create three beams. The center beam is used for focus and the two outside beams are used for tracking. The prism pair expands the read beams in one dimension to produce a circular beam. The relay lens, a doublet, forms an image near the beam combining mirror which lies at the end of the read laser path. The beam combining mirror sends the read light to the FTA.

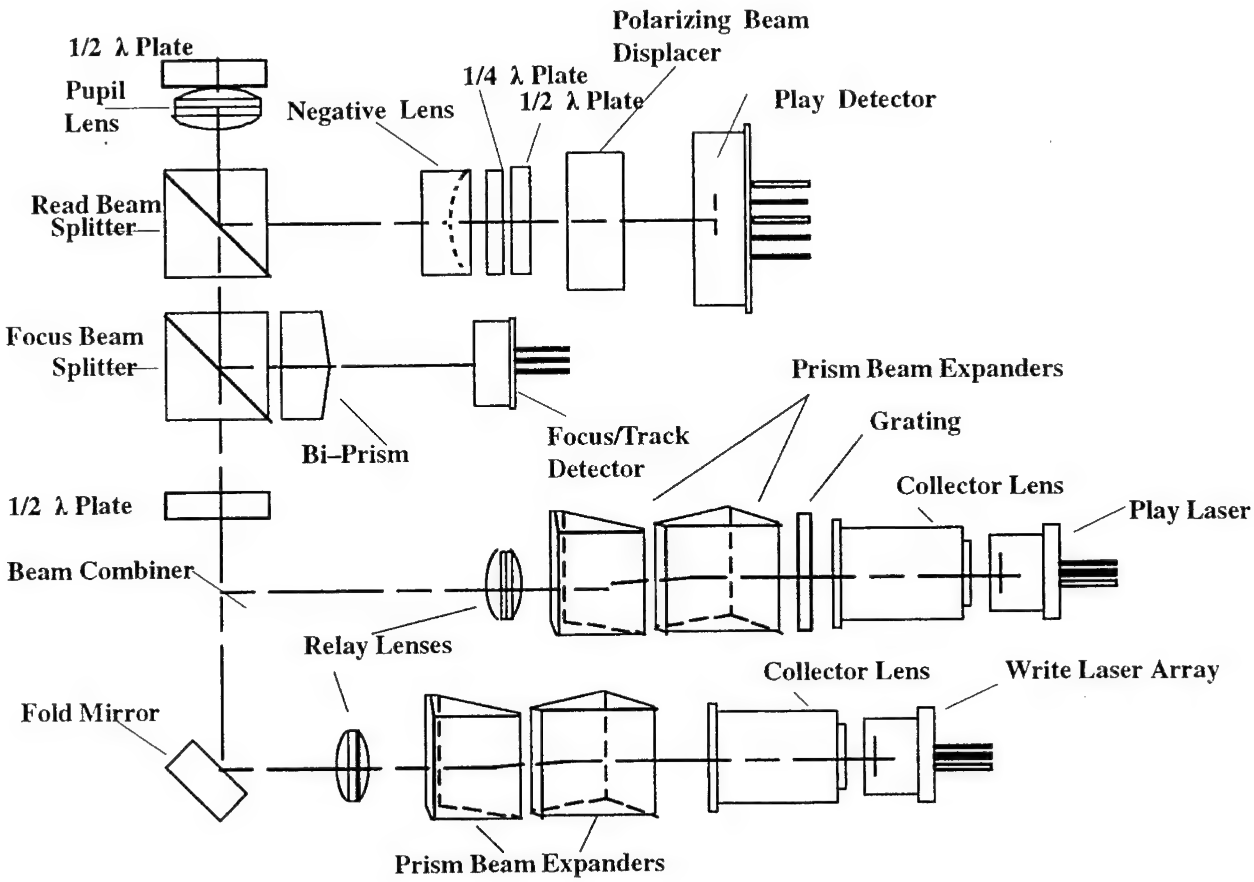


Fig. 3.3.1–3, Optical Head Components

Light from the two laser sources is combined at the beam combining mirror. Alignment between the two pairs of spots at this location is required in focus and across the track to allow read–while–write. Source alignment is performed by rotating the laser sources to set the track spacing. The relatively large magnification at this point is used to somewhat desensitize these critical alignments. The write and read beams then pass on up the path through the half wave plate which is used to convert the polarization of the lasers into the correct polarization to pass through the beam splitters. Then the combined beams pass through the focus and read beam splitters to the collimating lens, where they are recollimated, and then on to the micro–objective and disk. The micro–objective and disk are not shown in the schematic. Just before the light enters the micro–objective, a half wave plate is used to rotate the polarization of the combined beams. This places the electric field at the disk along the length of the groove. With the geometry present in the grooves, this optimizes the tracking signal while minimizing the focus disturbance.

For read, focus, and tracking, light reflected from the disk is split off by the read and focus beamsplitters and passes to the read and focus paths separately. In the read path, light passes first through half and quarter wave plates which are used to fine tune the polarization. The negative lens is used to magnify the image which falls upon the play detector hybrid PIN diode amplifier array. The polarizing beam displacer, which lies between the negative lens and the play detector, resolves the light into push pull signals, dependent upon the magneto–optic state of the area on the disk, which are detected by the detector array. Signals from the push pull elements for each of the two play channels are dif-

ferenced and sent to the read channel electronics and the tracking electronics. The detection technique has been described in section 4.2.

The focus detector path comprises the focus beamsplitter, the bi–prism and the focus detector. Focus is detected by the use of a double knife edge focus technique. The output from each of the array elements is sent to its associated preamplifier. The four signals are then summed and differenced and the resultant signals are input to the focus servo electronics.

3.3.1.1 Focus/Track Actuator

The FTA is a dual axis voice coil actuator that controls the position of the micro–objective lens. The vertical and horizontal position of the micro–objective lens determines the position of the write/read spots on the disk. The focus assembly is a moving coil design that moves vertically, mounted on spiral springs. The tracking assembly, which is mounted inside the focus assembly, is a moving magnet design that moves laterally on leaf springs.

3.3.1.2 Optical Head Electronics

The Optical Head Electronics (OHE) contains the interface circuitry to the electro–optics components in the optical head: focus/track and data detector preamps, read/write laser drivers and power monitor detectors. The OHE is a small printed wiring board mounted to the optical assembly. The OHE and the OHA ride on the translation stage, connected to the fixed circuitry at the Flexible adapter board by a flexible circuit ribbon cable.

3.3.1.3 Critical OHA Submodule Design

The following submodules and components of the OHA were considered critical to the functionality of the S/TODS. They represent areas defined in the Durable EDM contract as requiring further development. The FTA and LDA were identified as risk areas, studied and traded off. In this section, the designs as implemented and test results on the modular or component level will be discussed. The OHA submodules to be discussed are:

- Laser source modules
  - LDA and collector lens
  - Athermalization
  - Achromatization
- Beam expansion prisms
  - Achromatization
- Read While Write adjustment
- Polarization control
- Focus Track Actuator
  - Micro–objective
  - Actuator
- Focus and Tracking detection

3.3.1.3.1 Laser Source Modules

The Laser Source Modules are the assembly comprising the laser sources and the collimating optics. They have as their principal requirements:

Size	< 1 cu. in.
Output power:	
Read module	3 beams, 5 mW each
Write/Erase module	2 beams, 20 mW each
Modulation capability	
Write/Erase	app. 10 nsec. rise and fall pulse width 80 to 400 nsec. and CW.
Read	Low rate
Wavelength	810 to 830 nm
vs Temp.	normal diode laser shift
"instantaneous shifts"	< 5 nm
Wavefront (aperture @ 1/e2 intensity) (after beam expander prisms)	0.03 λ (0.02 λ goal) r.m.s. (focal shift allowed)

The Laser Source Modules have the potential to produce the largest temperature dependent contribution to spot deterioration at the disk. The decision was made for the S/TODS system to athermalize the LSM's. (The alternative was to temperature control the modules or portions of them.) This decision was driven by the availability of components that make such a design feasible. They are: 1. A commercially available LDA of 30 mW per element capability, demonstrated lifetime of similar elements operating at 100 mW that exceed 9000 hours. and extrapolate to more than 50000 hours. 2. An expected lifetime degradation with temperature of less than 3:1. 3. The commercial availability of cost effective collector lenses with low chromatic aberration and thermal focal shift.

3.3.1.3.1.1 Lasers

The Lasers in the S/TODS are semiconductor GaAs type lasers. This discussion is intended to be capability and peculiarity oriented, not laser design specific.

3.3.1.3.1.1.1 Read Laser

The Read Laser is a single element device. Its salient characteristics are:

Mount	TO-5
Power output	40 mW max
Wavelength	830 nm (nom.)
temp. dep.	0.2 nm / ^{0}C
power dep. shift	2 nm.
Lifetime	> 50000 Hrs @ 20 ^{0}C
Beam Characteristics	9 x 27 Deg. (nom.)
Drive requirements:	
current	130 mA (max.)
voltage	2.2 V (max.)
Noise	RIN < -120 dB/Hz @ 2 % feedback

3.3.1.3.1.1.2 Write/Erase Laser Diode Array

The Write/Erase Laser Diode Array is a two element device. Its salient characteristics are:

Mount	TO–5
Power output	40 mW max per element
Wavelength	830 nm (nom.)
temp. dep.	0.2 nm / ^{0}C
power dep. shift	2 nm.
Lifetime	> 50000 Hrs @ 20 ^{0}C
Beam Characteristics	9 x 27 Deg. (nom.)
Drive requirements:	
current	80 mA (max.)
voltage	2.2 V (max.)
Element separation	50 μm

As can be seen from the characteristics, the two sources are very similar. This has allowed use of a single LSM design. The particular parts used for the Read module are modified to allow the grating to be mounted directly in the module.

Two characteristics of the lasers cause significant design difficulty. First, the output beams are asymmetric. In order to utilize them efficiently, they must be corrected to have a circular cross section. Second, the wavelength of the lasers are not highly controlled and may wander depending upon temperature, age, and feedback conditions. The LSM design has considered these factors.

The asymmetric nature of the laser beam is corrected by the Beam Expansion prisms. Although they are not part of the source module, they will cause astigmatism to be added to the laser beams unless a high degree of collimation is maintained in the LSM. The tolerance for defocus of the Laser from the focal point of the collection lens has been allocated to be +/– 1.0 μm allowable.

3.3.1.3.1.2 The Collection Lens

The collection lens has two inherent potential problems. First, the focal length from the flange is not a constant as wavelength changes. Second, the focal length from the flange is not a constant as temperature changes. This will be the case for any lens. The Lens chosen for the system has a variation in focal length with wavelength of 0.1 um per nanometer of wavelength shift. For a 5 nm fast laser wavelength shift, this represents an acceptable shift of 0.5 μm. In addition to chroma shifts, there is a change in flange focal distance with temperature. Because there was no thermal data available from the manufacturer, a similar lens was modeled using CODEV. Utilizing similar materials, the flange to focal spot distance was calculated to move about 2 μm over a temperature range from 0 to 40 ^{0}C. This was based upon the material between the flange and the front surface of the laser in the LSM being Al, which is probably accurate to about 10 %. The primary changes of glasses are due to radii changes. As most glasses have expansion coefficients of from 6–8 in/in/^{0}C, and the lens housing is of Al, the model was felt to be reasonably accurate. The net focal shift projected is about 1 μm, as the wavelength shift of the light is compensatory.

3.3.1.3.1.3 LSM Tests

Tests were made of the LSM's after assembly. The system was assembled with a Prism Beam Expander in an oven. The laser was operated and its beam projected through an aperture in the side of the oven. Over the apertures required for the system, the results are tabulated in Table 3.3.1.3.1.3–1.

Table 3.3.1.3.1.3–1 LSM Tests

Temp. ^{0}C	Read Source		Write Source 1		Write Source 2	
	R.M.S.	Strehl Ratio	R.M.S.	Strehl Ratio	R.M.S.	Strehl Ratio
0	0.019	0.99	0.010	0.997	0.007	0.998
10	0.021	0.99	0.008	0.997	0.010	0.996
20	0.025	0.98	0.012	0.99	0.017	0.99
30	0.028	0.97	0.021	0.99	0.021	0.99
40	0.034	0.96	0.026	0.98	0.025	0.98
50	0.033	0.96	0.031	0.97	0.030	0.97

In interpreting these results, it is important to realize that 0.030 λ r.m.s. has been allocated to the LSM and Beam Expander. Thus, they should provide operation within specification over the temperature range 0 to 50 ^{0}C.

Comments about the results follow: 1. The aberration seen is dominated by astigmatism for the high temperatures. 2. At room temperature, the read module had some residual coma. Further investigation revealed that this was coma produced by wedge in the window. 3. Although best focus was set by translating through focus before epoxying the mount, there appears to be a focal bias. It would appear that the beam aberrations will be acceptable well below 0 ^{0}C. This would raise the expectation that with more careful alignment the temperature range can be expanded. The best interpretation of the data is that some shift in focal location was caused by stresses induced by the epoxy during cure. If a value can be predicted, this bias in focal position can be compensated before epoxying. It is certainly applicable to a production line setup.

3.3.1.4 Prism Beam Expander

The principal requirements for the Prism Beam Expander are:

Wavefront distortion (single wavelength)	<< 0.1 λ in 5 mm. dia.
Aperture	5 mm
Spot motion for 5 nm λ shift	< 0.01 dia.

The last is required in order to eliminate spot jitter along the read track with spontaneous wavelength changes. It was accomplished by achromatizing the prism pair. This was accomplished by a judicious choice of different glasses for the two 30 deg. right angle prisms. The input and output beams are maintained parallel under these conditions.

3.3.1.5 Read While Write Adjustment

The Read While Write adjustment is required to place the read spots following the write spots to high accuracy. The requirement allows +/– 0.1 µm displacement over a change in radius of 80 mm in order to maintain the optimum playback waveform. Allocating this equally between displacement from the radius and displacement at a radius means that the spots must move along a radius to an accuracy of +/– 0.1 mm. The accuracy of the RWW mirror adjustment is +/– 1 µm. This requires a stable mirror mount and accurate drive. In addition, the mount must maintain this position over temperature relative to a second set of spots having similar thermal induced motions.

3.3.1.6 Polarization Control

Polarization control is required in the system to allow operation to be optimized within the constraints of the OHA package. The polarization sensitive components are:

- The lasers
- Beam expanders
- Focus Beam Splitter
- Play Beam Splitter
- Disk Grooves
- Polarizing Beam Displacer

In addition, there are 3 half wave plates and 1 quarter wave plate in the system to control polarization.

The output of the lasers is highly polarized. The direction of the electric field is in the plane of the junction. This is the narrow dimension of the output beam. When image on the disk, the write spots lie principally along the disk. Without further control, the polarization would lie along track.

The Prism Beam Expanders are designed to take advantage of Brewster's angle where there will be no reflection for polarized light. The laser is properly polarized to allow this orientation for the design.

The two beam splitters are cubes. The beamsplitting surfaces lie at 45 deg to the input beams. The laser beams pass through the beamsplitters on the way to the disk. Upon return, some of the light is split off at 90 degrees to allow operation of the focus/track and read Detectors. Thin films have one general property that creates difficulty in polarization. They will always have a lower reflectance for electric fields lying in the plane of reflection than in the perpendicular plane. Construction the OHA in a single plane requires the laser polarization to be in the high reflectance form unless converted. For the Read Beamsplitter it is required that it have high reflectance for the non–transmitted polarization and about 12 % reflectance for the transmitted polarization. To allow this orientation, a half wave plate is used just before the beamsplitters.

The groove on the disk is used to derive tracking and format read signals. In order to accomplish these objectives, the beam steering as the spot crosses the track (the push–pull ratio) and the modulation percentage must be controlled. The requirements are:

Push–pull signal	$0.4 < (I_1 - I_2) / I_0 < 0.65$
Track cross signal	$0.5 < (I_1 + I_2) / I_0 < 1.00$

These values provide a large tracking signal and a track crossing signal that will not impede the ability to focus to an unmanageable extent. The manufacturer has the most experience making geometries to operate with the electric field lying along the groove length. In order to facilitate disk manufacture, a half wave plate was placed between the tube lens and the micro–objective to allow this orientation to be achieved.

3.3.1.7 Micro–Objective

A custom Micro–objective was designed and built for the system by a subcontractor. The optical requirements come from system studies and allocations. The requirements for relatively large flat field and a degree of achromatization are particularly challenging. The mechanical size require-

ments have been derived from preliminary design of the FTA. A summary of the specification follows:

Numerical Aperture	0.65
Focal Length	3.1 mm
Wavelength	810 to 850 nm
	λ +/– 5 nm instantaneous bandwidth
Field of view	+/– 80 µm
Cover glass	1.213 +/– 0.025 mm
Working distance	> 1 mm
Long conjugate	infinite
Weight	< 3 gms (2.3 as delivered)
Barrel dimensions	9 x 14.5 mm
R.M.S. wavefront	< 0.05

The lens as delivered met all of the requirements. Tests of the optical performance showed performance as good as r.m.s. 0.019 waves on axis with the required glass thickness. When operated 1 deg. off axis, the lens maintained a performance of 0.03 waves. 1 deg. off axis is 55 um off axis. The field flatness was also confirmed in these tests. Full performance was maintained without refocussing.

3.3.1.8 Focus Track Actuator

The Focus Track Actuator was developed for the S/TODS system. The major design requirements for the FTA are:

Dual Axis Actuator (Focus and Track)	
Travel	
Focus	+/– 315 µm
Tracking	+/– 75 µm
Mass of lens	about 3 gms.
Bandwidth	2.5 kHz, Closed loop, both axes
First resonance producing spot motion	>10 kHz
Tracking axis lens position sensor	
Environment	DDU

The design approach taken to build the FTA was to first chose the most appropriate design type. Then, create finite element models (FEM) of major assemblies and evaluate performance. Next, design, fabricate and test a prototype using a test bed dedicated to the FTA development and capable of testing the critical parameters. Use the design feedback to achieve a solid final design.

Individual motors are required for the two motions. Tracking employs moving magnets attached directly to the micro–objective. Fixed coils are attached to the body of the FTA. The has the advantages of low moving mass, no flexing of wires and good heat sinking of the coils. Focus reproduces typical loudspeaker design. The Focus motor employs a moving coil in the cylindrical gap of a fixed permanent magnet.

The tracking position sensor uses a moving flag. A fixed LED detector pair senses the motion of the flag. The LED and detector are mounted to the FTA housing. This geometry is relatively insensitive to coupling from the focus axis.

The FTA requirements were expanded to develop the specifications for the FTA. The preliminary FTA, (FTAX–x) was then constructed. After some redesign to achieve performance, the final specifications were established. They are:

Optics:	
Numerical aperture	0.65
Working Distance (mm)	1.0 min.
Diameter (mm)	9.0 max.
Length (mm)	14.5 max.
Mass (gms.)	3.0 max.
Location of Center–of–gravity	within 0.25 mm of geometric center
Tracking:	
travel (µm)	+/– 80
Moving mass (gms)	3,0
Natural frequency (hz)	90
Peaking	10 dB
Sensitivity @ 1 Hz in µm / A	139
Force constant N/A	0.056
Stiffness (N / mm)	0.96
Focus:	
Travel (µm)	+/– 315
Moving mass (gms)	7.1
Natural frequency (hz)	72
Peaking	8 dB
Sensitivity @ 1 Hz in µm / A	1170
Force constant N/A	1.72
Stiffness (N / mm)	1.47
Physical:	
Total mass (gms.)	49
Size (app.)	1.25 D. x 0.775 inches
Center line to edge	0.625 in.

3.3.1.8.1 Finite Element Modeling

Finite Element Modeling (FEM) analysis was used as a tool to predict the performance of the FTA and to aid in its optimization. Major subassemblies including the tracker and focus suspensions were modeled. The analysis then used to find undamped natural frequencies and the response of the suspension to harmonic input. Then the response of the suspension with damping materials was modeled to evaluate its performance with harmonic input. This proved particularly useful in diagnosis of problem resonances. An example of a potential problem resonance is shown in Fig. 3.3.1.8.1–1

In this figure, a potentially disturbing mode at 805 Hz is clearly seen. This mode results from twisting in the leaf spring suspension. It was suppressed by the use of damping material.

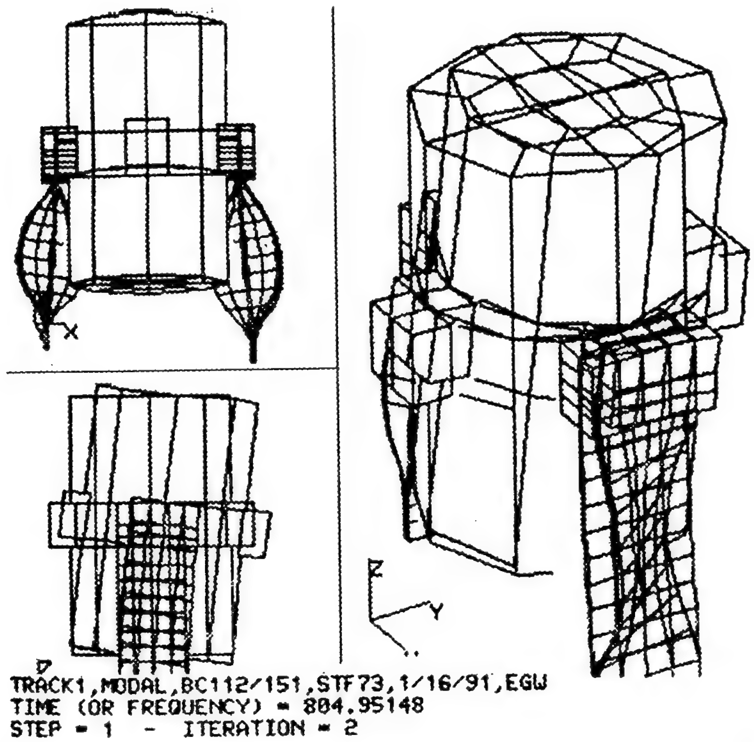


Fig. 3.3.1.8.1–1, Modal Analysis of Tracking Suspension Showing Twisting Mode

3.3.1.8.2 Model Testing

A preliminary model of the FTA, FTAX–1 was constructed. This represented the best design judgment of the eventual form. A test lens was installed and the FTA was tested in a testbed. A schematic of the testbed is shown in Fig. 3.3.1.8.2–1.

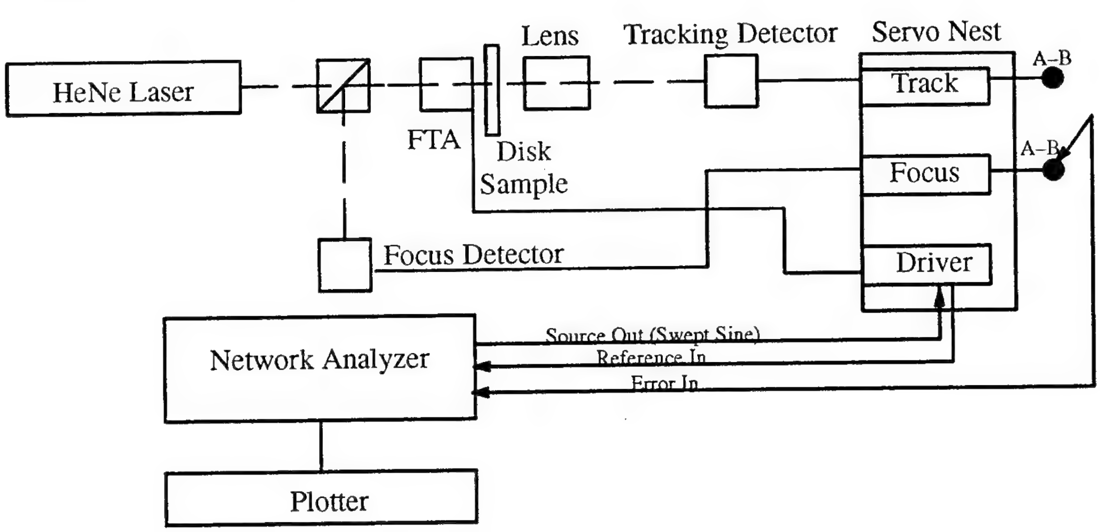


Fig. 3.3.1.8.2–1, FTA Tester Functional Layout

The testbed was used to plot the transfer functions of the FTA. A typical output is shown in Fig. 3.3.1.8.2–2

This figure shows the transfer function of one of assembly variants. It shows a fundamental resonance at 52 Hz and a troublesome resonance at 2.5 kHz.

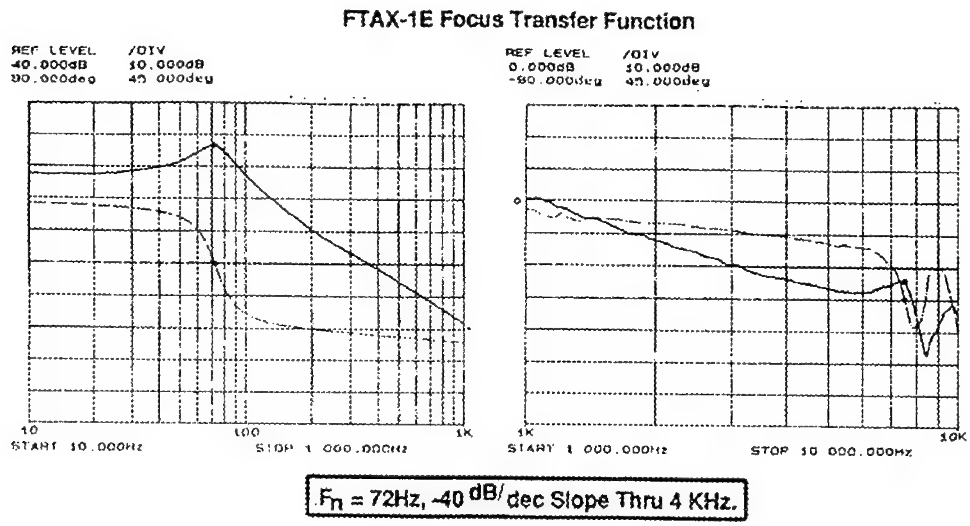


Fig. 3.3.1.8.2–2, FTAX–1E Focus Transfer Function

A series of tests with variants of the tracking and focus springs are summarized in Table. 3.3.1.8.2–1

Table 3.3.1.8.2–1 FTA Test Performance

VERSION	NATURAL FREQ. (HZ)		PERFORMANCE
	FOCUS	TRACKING	
FTAX–1A	NA	53	–40dB/decade through 9 kHz (tracking only)
FTAX–1B	34	53	–40dB/decade through 9 kHz (tracking) weak response above 3 kHz; visible spring resonances at 500 Hz with resulting energy loss (focus)
FTAX–1C	53	52	–40dB/decade through 9 kHz (tracking) response increased to 7 kHz; resonance at 2.1 kHz and 5.4 kHz (focus)
FTAX–1D	53	72	–40dB/decade through 9 kHz (tracking) response increased to 9.5 kHz; resonance at 2.1 kHz (focus)
FTAX–1E	90	72	–40dB/decade through 3 kHz; resonance at 7.8 kHz (tracking) –40dB/decade through 4 kHz; resonance at 7.5 kHz (focus)

These changes are variants in the thickness and damping in the springs. The final version, FTAX–1E, was operable at the required servo bandwidths. The resonances seen were sufficiently damped that they could be dealt with in the servo without compromising system performance.

The final versions of the FTA, FTA–2, which were constructed for the S/TODS system carry most of the properties of FTAX–1E. Revisions were made to increase the tracking force constant by in-

creasing the size of the coil. Also, in FTA–2, the track position sensor was added. The design has been very successful and has functioned as intended in the system. FTA–2 is shown in Fig. 3.3.1.8.2–3.

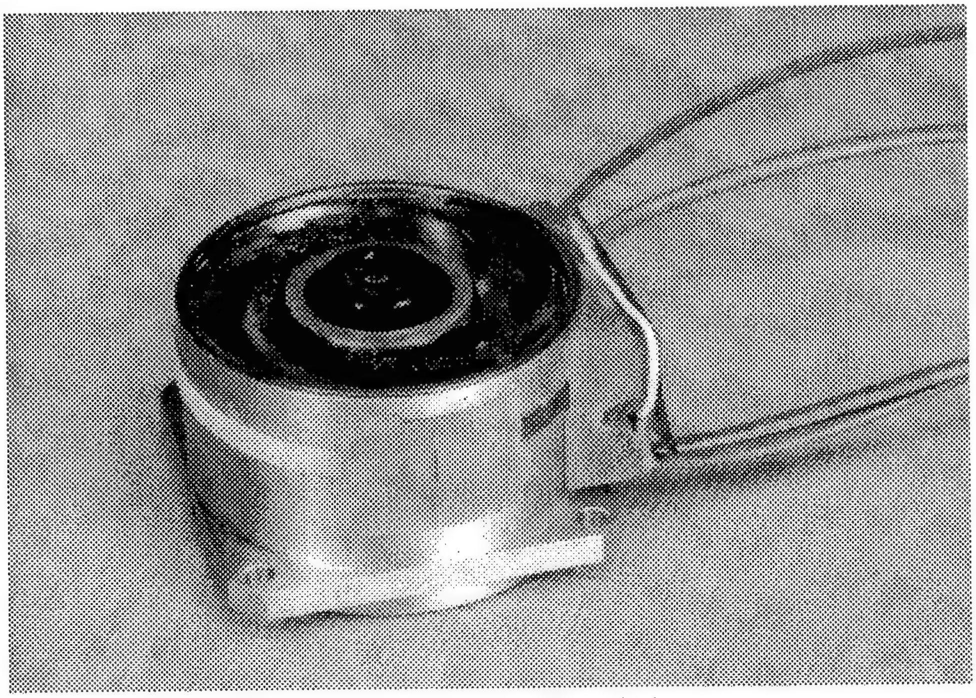


Fig. 3.3.1.8.2–3, Focus/Track Actuator

3.3.1.9 Focus and Tracking Detection

Focus and Tracking Detection is accomplished using a double knife edge focus detection and push–pull track error detection. The creation of a track location dependent motion of the return beam from the media has been discussed in the Media section.

Track error is detected by splitting the return beam after the return beam is sampled by the use of a bi–prism. The track error is detected by summing each of the bi–cells in the Focus/Track detector and the taking the difference.

The focus error signal is generated by using each side of the bi–prism as a knife edge. An error function is generated for each side by taking the difference in each bi–cell. These two differences are summed to produce the Focus Error curve. This technique has been selected for relative insensitivity to track crossing and beam wander. It also lends itself to detecting only the track crossing and focus error of the center spot of the array. To operate properly, the beams must be in focus at the detectors and centered on the transition regions. The separation of the spots to place them both on the transition regions of the detectors is controlled by the separation of the detectors and the bi–prism. Focus is controlled by the separation of these two elements from the tube lens.

3.3.2 DISK DRIVE UNIT MECHANISMS

3.3.2.1 Magnetic Bias Device

The S/TODS employs a single iron core electromagnet to provide a bias field for writing or erasing on the disk. The magnet has sufficient size to cover the entire recording zone without movement. The magneto system requires that a magnetic field of 200–400 gauss be applied perpendicular to

and through the magneto–optic recording layer on the disk. Three states of magnetic flux bias are employed: forward bias for record, reverse bias for erase and no bias for read. The magnetic bias device is mounted to the loader and during operation is placed on the opposite side of the disk from the optical head.

3.3.2.2 Translation Stage

The translation stage (LTSS) is a precision linear motion device. The design issues have been discussed in Section 2.10. The LTSS as delivered met the design goals for the system. The optical head is mounted to the moving platform of the stage. The translation stage precisely moves the optical head radially across the disk surface to act as a coarse positioner of the optical head's micro–objective lens.

3.3.2.3 Spindle/Vacuum Chuck

The optical disk is rotated by a precision (ball bearing type) motorized spindle whose parameters conform to the results of the design analysis described in Section 2.7. The optical disk centering cone and vacuum chuck, whose parameters conform to the results of the design analysis described in Sections 2.8 and 2.9 are mounted directly to the spindle shaft. Vacuum from a pump in the Disk Drive Unit is supplied via the hollow spindle shaft to firmly hold the disk to chuck during spindle rotation.

3.3.2.4 Loader

During disk load and eject operations, the disk is moved through the Disk Drive Unit under control of the loader. The loader accepts the disk with the cartridge, separates the disk from the cartridge and loads the disk onto the spindle. The exact opposite occurs on a disk eject command and the loader presents the disk with carrier to the Disk Accessing Mechanism for storage. The loader accepts commands and sends status to the Electronics Unit via the DDU Control Module. The loader is attached to the deck structure, as are the spindle and translation stage.

The basic requirements for the Loader include:

Media can not be damaged	
Cycle time	< 10 sec.
Temperature range	0 to 46 ^{0}C
Maximum height	4.0 in.
Light weight	
Rugged	
Low center of gravity	
Interference with drive	none
Position magnet	
Adaptable to jukebox	
Designed for cost effective manufacture	

The Loader as constructed has been examined for failure modes that would damage the Media. No modes were found that could cause damage. The cartridge is inserted manually through the slot in the front of the DDU. Light sensors are used to verify the location of the cartridge and to verify that it has reached appropriate locations. Friction drive is employed to handle the caddy. The disk is loaded onto the hub by a combination of driven motion of the carrier down and a pusher located inside the minimum recording radius. Compliant coupling between the forcing elements is used to

protect the disk. The disk is released by the carrier as it contacts the centering cone on the spindle. The disk is constrained by the centering cone and pusher until it is brought into contact with the chuck. During this final load motion the carrier continues to be opened to provide rotation clearance. Optical sensors are used to detect that the disk has arrived at the chuck and vacuum is applied. Once vacuum is sensed at the chuck, the pusher is retracted and the operational position of the bias magnet is achieved. This Loader has operated without problems throughout testing. Operation was without problems throughout vibration testing and flight test. See photo of Loader in Figure 3.3.2.4–1.

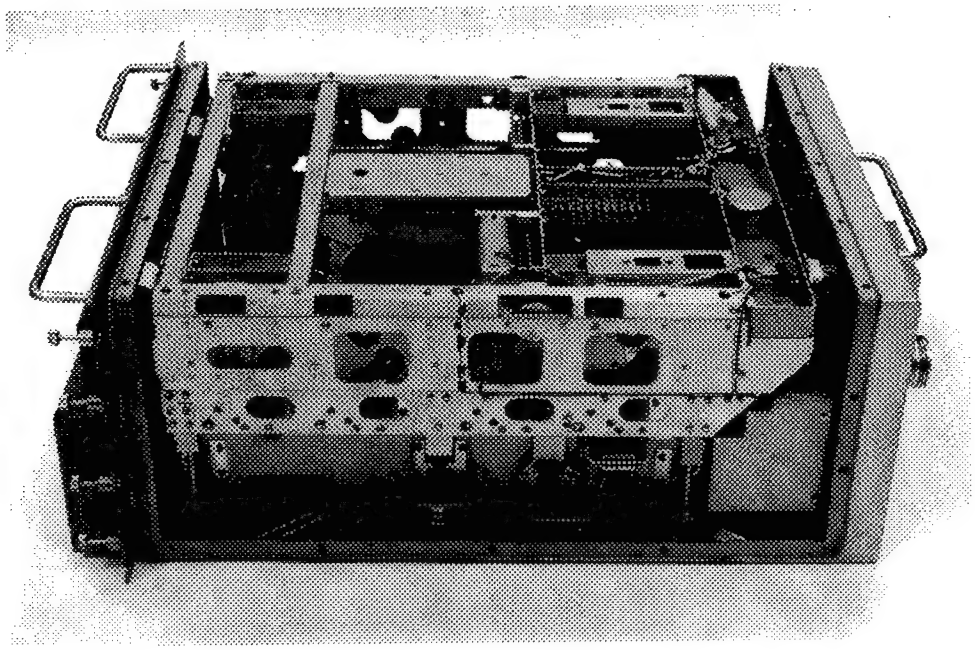


Fig. 3.3.2.4–1, Loader

3.4 DECK ASSEMBLY

The deck assembly is the structure which rigidly locates the Spindle, Translation Stage, Disk and Optical Head in proper alignment. It also forms the platform for mounting the loader and vibration isolators. The deck structure follows the design issues discussed in Section 2.6 utilizing a lightweight highly damped Mg casting and a lightweight aluminium sheet metal support structure. The vacuum system accumulator tank is housed below the sheet metal on the right side.

3.5 PACKAGING & ENVIRONMENTAL CONTROL

The chassis is the interface between the deck and the equipment rack. The wire rope shock and vibration isolators are mounted between the deck and the chassis. The chassis is hard mounted to the rack via the front panel and shock pins in the rear. The chassis follows EIA mounting and size requirements of a 10.5 inch tall front panel by 24 inches deep and 17.75 inches wide. All cabling for the unit exists from the rear wall of the chassis. Cooling air flows from the front of the unit to the rear. The fan and filter are mounted on the front panel behind the doghouse. The vacuum pump and isolator feet mount to the reinforced "x" bracing in the bottom of the chassis. Because of the size of the disk and ultimately the drive, the cover was designed to be removed for installation and access of

the drive into the chassis. The cover is metal. It is provided with a gasket to form an EMI shield with the chassis.

3.6 ELECTRONICS UNIT

The Electronics Unit (EU) contains all of the modules necessary to operate the S/TODS. The EU is comprised of four major subsystems: the Control/Interface Processors , the Data Formatting Electronics, the Drive Control Electronics and the Power Supplies.

The EU configuration is based upon IEC standard Versa Module Extended (VME) system architecture for control. The physical form is based upon the use of the Euro–Card physical standard. the module height is 160 mm. Procured digital modules are all of the 6U (double width) standard card. There are two procured analog modules. The Spindle Controller uses a 6U card. The Stage Controller uses a 9U (triple width) standard card. All custom S/TODS modules employ 9U standard cards. In Fig. 3.6–1, the location of the individual cards is shown.

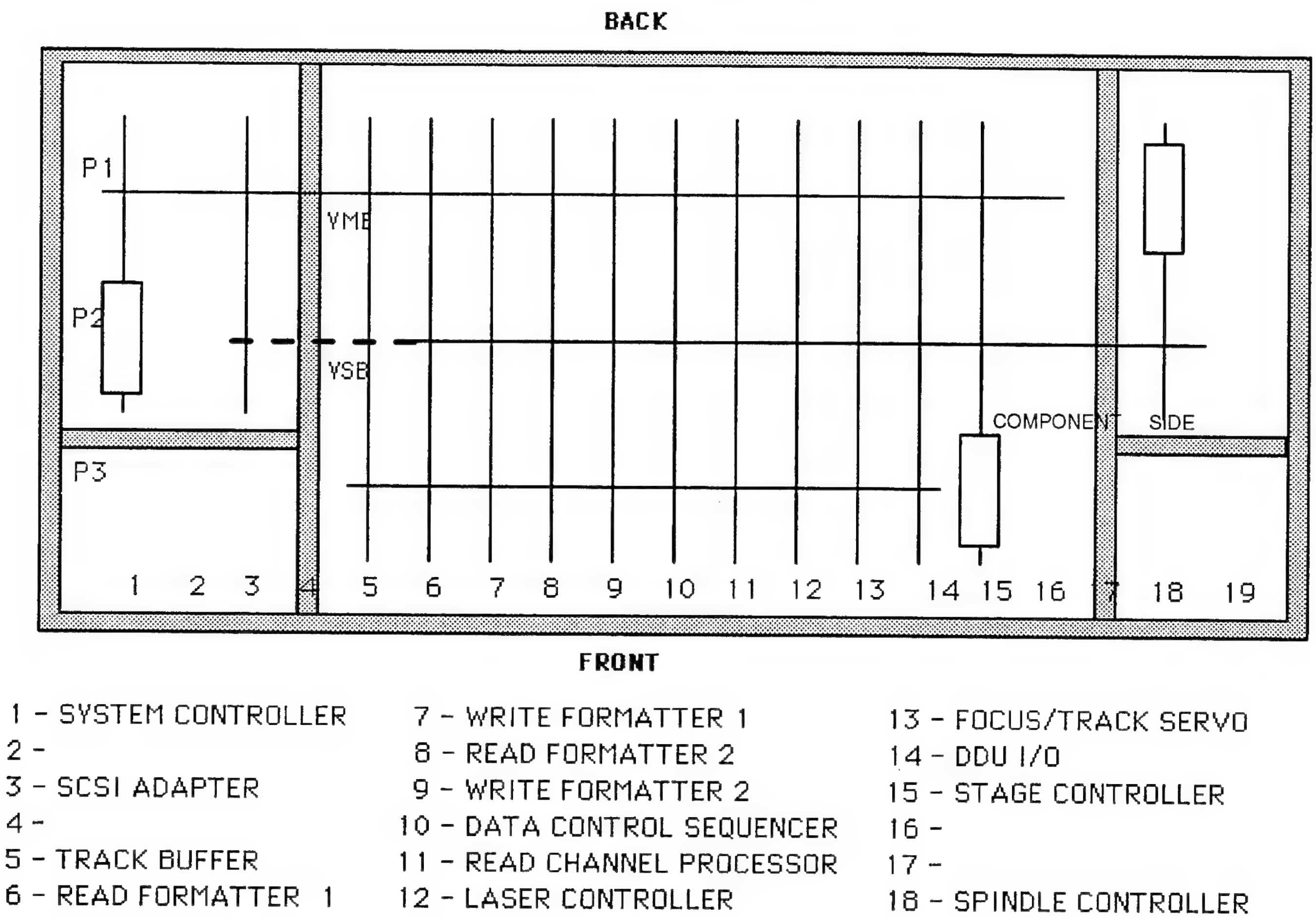


Fig. 3.6–1, EU Nest Locations

The EU backplane employs a procured VME bus and custom developed I/O busses. The custom buses are a VME Subsystem Bus (VSB) and a bus that handles all non–standard signals.

The VME system bus (P1) is the primary mode of communications within the EU and accesses all of the S/TODS modules. It is a structure that support up to 21 modules (S/TODS has 11). There is a 16 MB (32 bit) address range. The bus supports asynchronous non–multiplexed data access and multi–master arbitration with 7 interrupt levels. S/TODS employs this bus using a single master control processor (the System Controller). Transfers are all non–blocking. Transfers on the VME bus are restricted to 8 and 16 bits.

The second bus (P2) provides I/O communications dedicated to the custom VME modules particularly the data formatting and DDU control/interface modules. The VSB bus provides local EU module communication along with a dedicated data transfer bus. This off loads the VME system bus for time critical transfers and provides SCSI access to the track buffer and user data.

The third "bus" (P3) is employed to handle any other signals. These include ECL, analog and low noise signals and miscellaneous signals that must be transmitted between the custom S/TODS modules.

3.6.1 POWER SUPPLIES

The Power Supplies can be summarized as follows:

2 single output units 48 V

1 multiple output unit, +5, + 15 and – 15 V.

1 multiple output unit, – 5 and +28 V.

All of the supplies operate from either 400 Hz 110 VAC or 60 Hz 110 VAC. They are forced air convection units and feature high efficiency with low weight and size. They are Mil compliant.

3.6.2 EU DESCRIPTION

Figure 3.2–1, S/TODS Block Diagram, shows the partitioning of the EU and its subsystems.

3.6.2.1 Control/Interface Processors

3.6.2.1.1 System Controller

The S/TODS System Controller (SC) provides centralized control and monitoring of all subsystems. The module is responsible for initiation, completion and status reporting of internal activity. A Radstone PMV68–CPU–1A Single Board Computer incorporating a Motorola 68020 CPU performs the SC function.

In normal operation, the SC receives the particular command block sent from the host after being parsed from the SCSI input data bus. The command is interpreted and all necessary setup and inter–module coordination is managed by the SC module. The SC handles all error and exception conditions that may occur and takes the appropriate actions necessary to resolve them. When the requested operation is completed, the SC creates a return status parameter block for transmission back to the host. This acknowledgement follows the transfer of any requested user data between the host and the S/TODS.

3.6.2.1.2 SCSI Adapter

The SCSI Adapter has control through Software of the System Functionality. The functions for which it is responsible are:

SCSI standard computer interface
Accepting SCSI commands, messages and user data according to
ANSI X3.131–1986 SCSI Standard

The Software for these tasks resides in the SCSI hardware. The SCSI hardware consists of a Radstone SCSI–11 board. This board includes interfaces to the SCSI bus, the VME bus and the VSB bus. It uses a Motorola 68020 processor. A 64 K EPROM is used to hold the adapter program memory. A 1 M RAM is employed to hold the executing SCSI Adapter program, scratch pad, and a shared memory between the SCSI Adapter and the System controller.

3.6.2.2 Data Formatting Electronics

The data format has been described in Section 2.3.1. The Data Formatting Electronics takes data from the VSB bus, provides the necessary buffering and adds the format overhead. It also controls the sequencing of operations under control of the SC through the VME bus. For playback, it takes the data with overhead from the Read Channel Processor, strips the overhead, applies EDAC and Buffers the output through the VSB to the user.

3.6.2.2.1 Track Buffer

The Track Buffer module allows the user to write and read data at any rate up to the maximum specification for continuous and burst transfers. A block diagram of the Track Buffer is shown in Fig. 3.6.2.2.1–1.

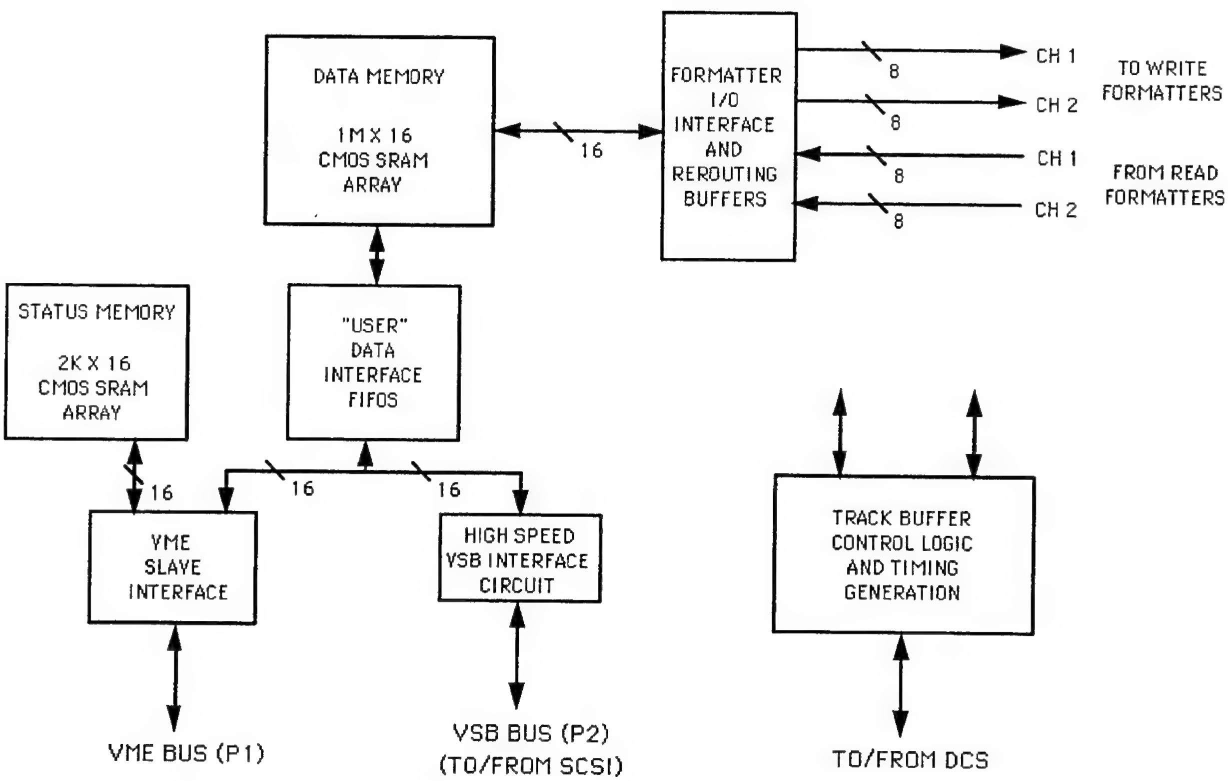


Fig. 3.6.2.2.1–1, Track Buffer Block Diagram

The module Data Memory capacity supports user burst lengths of 3 Mbits at the maximum transfer rate. The Write and Read Formatting modules interface to the Track Buffer module at the internally

synchronized disk rate through the Formatter I/O Interface and Rerouting Buffers. This is accomplished under control of the Track Buffer control logic and timing generation from the DCS. The User Data is coupled over the VSB interface into the Data Interface FIFOs. Control of this data transfer is under the aegis of the VME bus and the SC. This decoupling of user transfers from disk accesses provides the means to write or read large quantities of data blocks over the host interface, up to an entire disk side without interruption. For example, during a write operation, the user may immediately start loading data simultaneous with the mechanism access and seek processes. This eliminates the inefficiencies of SCSI disconnects after a Write command has been received by the S/TODS. The Track Buffer provides the following:

Greater than 2 revolutions capacity
Accommodates transparent band changes
5 fully programmable capacity "thresholds"
    manage under or overflow conditions
Burst data transfers based on thresholds
Dynamic threshold level and sense adjustment

Write operation requirements
    preload to avoid processing latency
    track threshold to assure full track recordings
    flow control by the SC

Format operations during disk certify
    test data pattern from the SC
    Override sector and track thresholds
    Write until SC stops operation
    Test pattern is cycled

Read operations
    Data flow controlled by SC through use of "flow" thresholds
    Minimum user data block is 16 kB.
    SCSI notifies SC about block transfers by itself between user and track buffer
    SC keeps track of block designations being made between formatters and
        track buffers

3.6.2.2.2 Data Control Sequencer

The Data Control Sequencer (DCS) is a central control module that directs the low level, time–critical processes during all operations. The DCS provides the EU with all clocking, gating and control signals required to perform the formatting, deformatting, encoding and decoding of the data as well as managing Track Buffer operation during disk accesses. The DCS generates the reference frequencies used to operate the system. The DCS processes pilot track data, clock, and mark outputs from the RCP.

A top level Block Diagram of the DCS is shown in Fig.3.6.2.2.2–1 to illustrate the system partitioning.

The Reference Generator provides all the system clocks. DCS Write Signal Generation coordinates the write operations and creates the necessary control signals. DCS Read Signal Generation coordi-

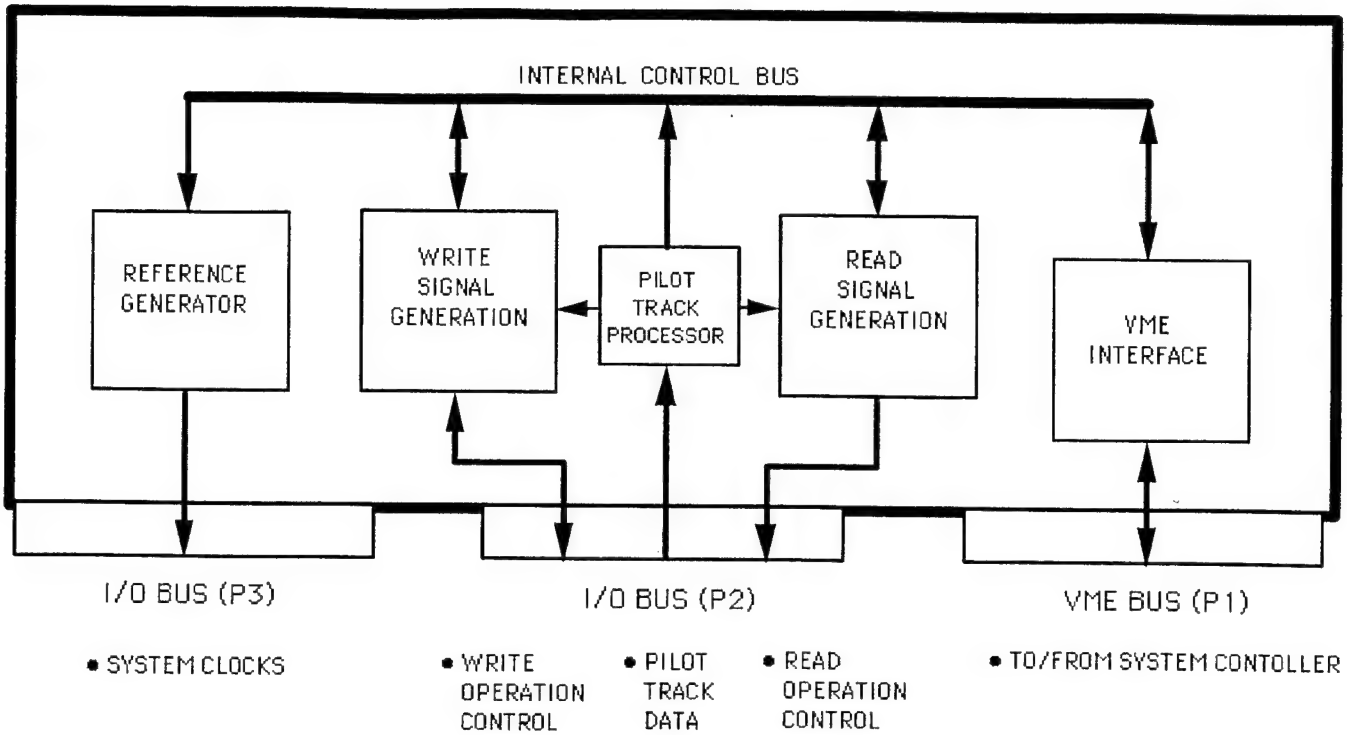


Fig. 3.6.2.2.2–1, DCS Block Diagram

nates the Read operations and creates the necessary control signals. Pilot track processor takes the pilot track data. It generates the appropriate interrupts to notify the system controller that track and sector marks were received. It checks The CRC field to confirm the accuracy of the address and provides pilot track address as a status to the System Controller. The VME Interface provides status reporting and control.

3.6.2.2.3 DCS Write Signal Generation

DCS Write Signal Generation is shown in Fig. 3.6.2.2.3–1.

The control signals necessary for the Write operation require a number of inputs. Among these are the write byte clock, track mark, track threshold, sector threshold, the number of sectors/revolution, operation enable and mode designations such as erase and format. Write control signals are the output of the DCS Write Signal Generation. Proper sequencing must be maintained for the system to operate. Preload of the write formatters occurs when the track buffer contains one sector of data. Operation begins at track mark when write operation is enabled and track threshold is asserted. Control signaling is based on byte, sublock, sector, column, and row counters generated with respect to the track mark.

3.6.2.2.4 DCS Read Signal Generation

DCS Read Signal Generation is shown in Fig. 3.6.2.2.4–1.

The control signals necessary for Read operations require a number of inputs. Among these are the write byte clock, track mark, the number of sectors/revolution, operation enable, PDL and mode designations, read or format. Read control signals are the output of the DCS Read Signal Generation. Proper sequencing must be maintained for the system to operate.

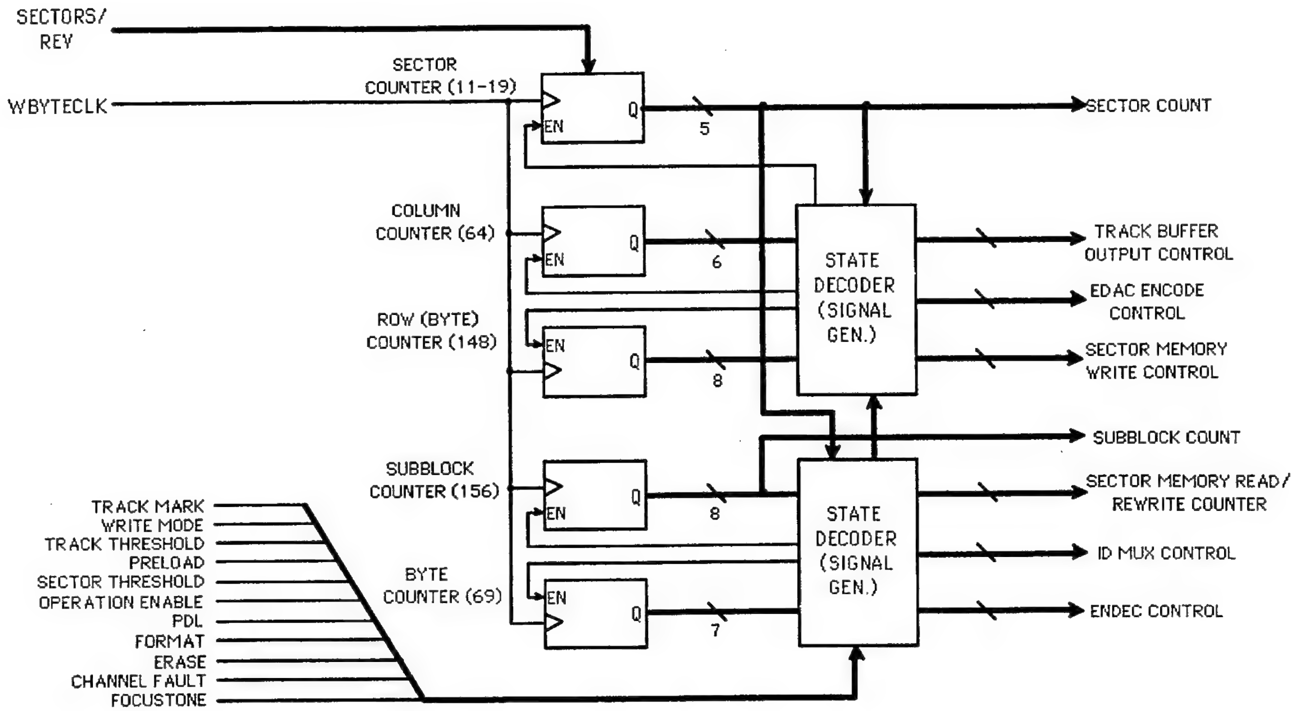


Fig. 3.6.2.2.3–1, DCS Write Signal Generation Block Diagram

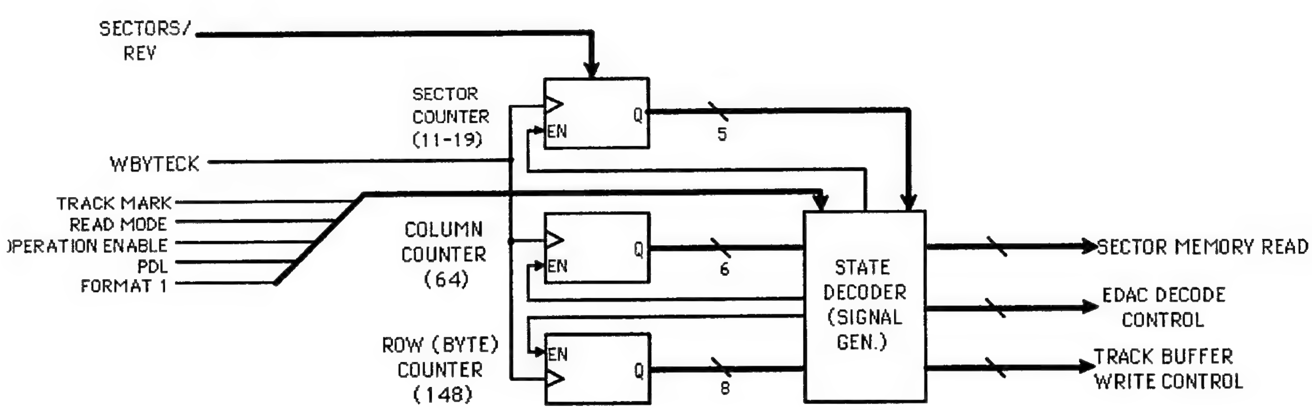


Fig. 3.6.2.2.4–1, DCS Read Signal Generation Block Diagram.

3.6.2.2.5 Reference Generator

The System Clock Reference Generator provides all the S/TODS reference frequencies. All frequencies are derived from a 50 MHz ECL clock source. Band dependencies for the spindle clock and the pilot track PLL reference clock are commanded from the SC through the VME interface. The fixed frequencies needed for Formatter and Buffer clocking are:

Write Symbol Clock	25.0 MHz square wave
Write Byte Clock	2.0833 MHz square wave
Rewrite Clock	8.33 MHz 33 % duty factor
Track Buffer Cycle Clock	6.25 MHz square wave

3.6.2.2.6 Write Formatter

The S/TODS Write Formatter block diagram is Fig. 3.6.2.2.6–1.

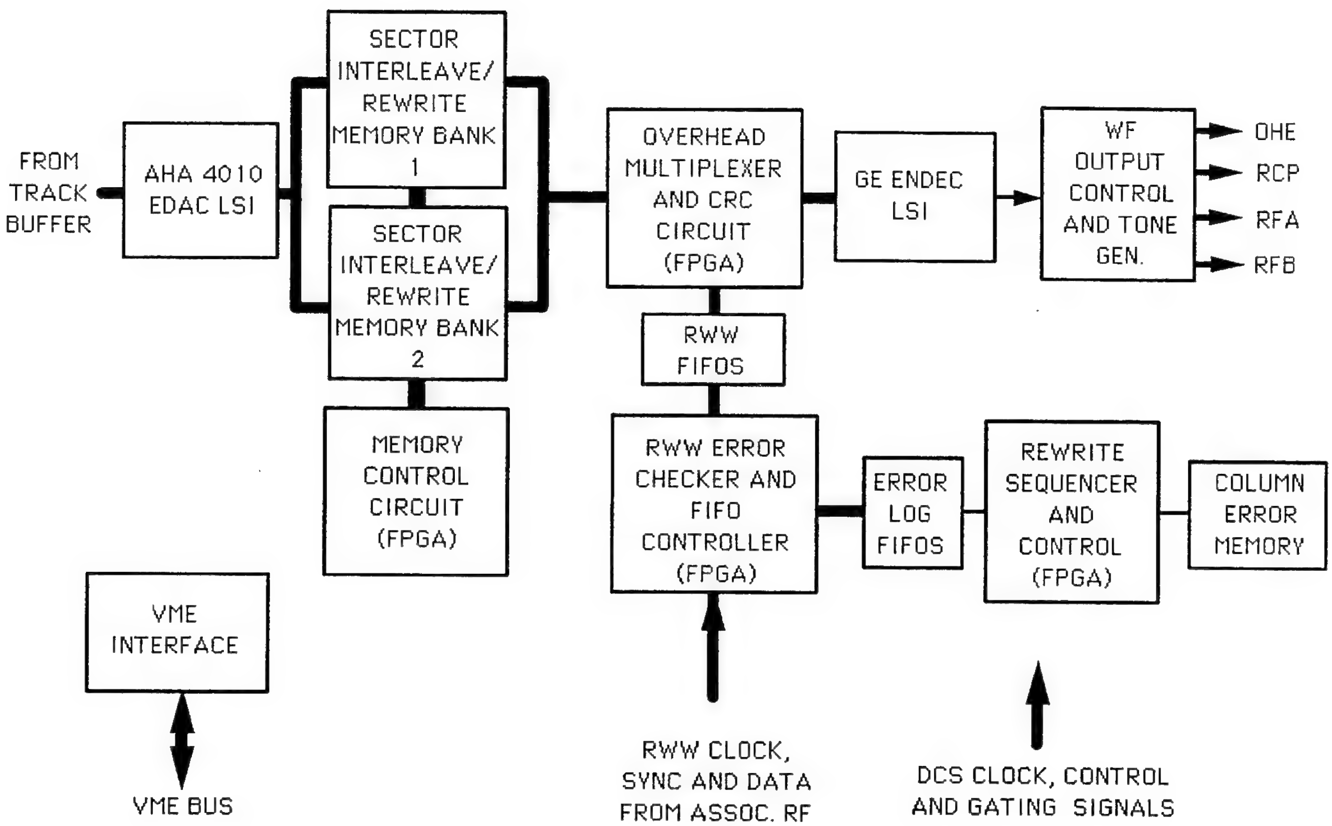


Fig. 3.6.2.2.6–1, Write Formatter Block Diagram.

The S/TODS Write Formatter accepts user data from the Track Buffer, performs EDAC encoding using the AHA4010 EDAC LSI. Next byte interleave is performed and the data is stored for possible rewrite. The module then partitions the data into the sector and sublock format. Then addressing and overhead insertion is performed. The resultant data is serialized and encoded using the 3 Phase (1,7) algorithm and written onto the disk, using the write clock source. The write data is also buff-

ered (delayed) and compared to read data from the disk via the RWW circuitry. This permits checking the recorded data integrity and determines if a sublock must be rewritten. All of this is controlled through the VME bus with the timing signals from the DCS and the Read Formatter.

3.6.2.2.7 Read Formatters

The S/TODS Read Formatter Block Diagram is Fig. 3.6.2.2.7–1.

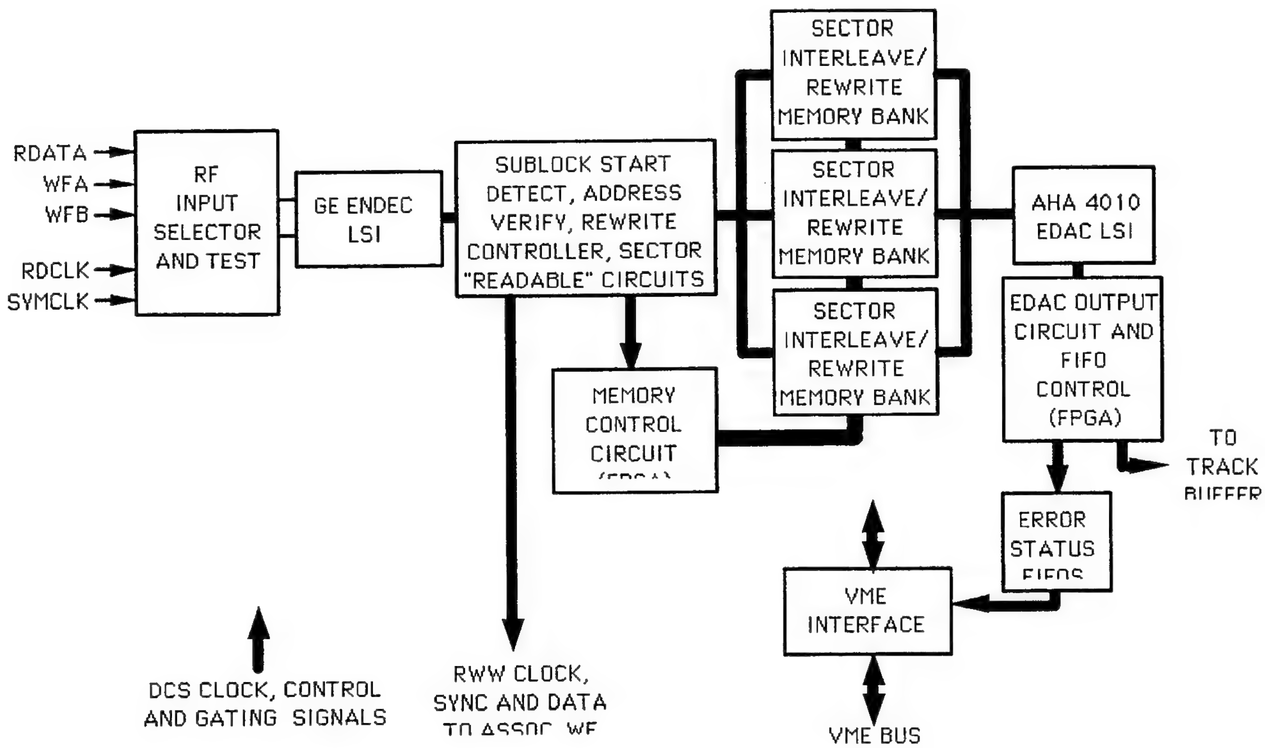


Fig. 3.6.2.2.7–1, Read Formatter Block Diagram.

The S/TODS Read Formatter takes the recovered read data and clock from the Read Channel Processor module. It decodes the (1,7) encoded data and converts it to parallel format using the ENDEC LSI. The data is then stripped of its address and overhead. Then it is deinterleaved in the interleave memory bank. It is EDAC decoded using the AHA 4010 EDAC LSI and loaded into the Track Buffer module. The Read Formatters also decode the Header sublock information and send it to the DCS and System Controller to synchronize and coordinate the playback processes. Control and gating operations are controlled by the DCS. Overall control and reporting is through the VME Bus. All operations are directed on a track basis.

3.6.3 DRIVE CONTROL ELECTRONICS

3.6.3.1 Laser Controller

The S/TODS Laser Controller Block Diagram is Fig. 3.6.3.1–1.

The Laser Controller includes circuitry for voltage and drive current regulation for the write and read laser sources. The module generates constant current bias and pulse drive levels for the laser diode

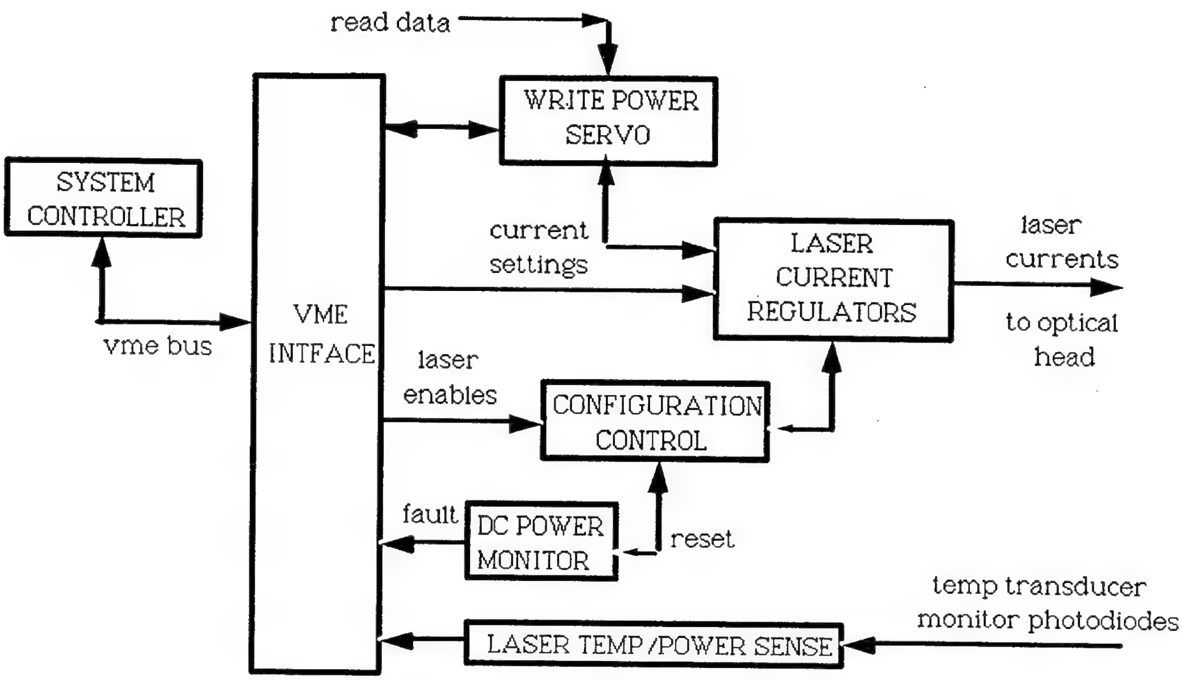


Fig. 3.6.3.1–1, Laser Controller Block Diagram.

drivers located in the optical head in the DDU. Control is exercised by the SC through the VME interface. The write laser currents are fine tuned by the write lasers' power servo circuit during write operations. This closed loop system uses RWW feedback to optimize the pulse fidelity by fine tuning the drive current to account for media sensitivity, laser efficiency, optics efficiency and disk rotational rate variances.

3.6.3.2 Focus/Track Servo

The Focus/Track Servo (FTS) module contains four operational subsystems: the focus servo, tracking servo and radial position servo. The module subsystems control the dual axis actuator in the optical head. The focus servo maintains a constant distance between the objective lens and the disk surface. It corrects axial runout and disk deflection errors and is designed to focus over a wide range of disk reflectivities. The tracking servo insures data integrity by centering the write lasers and read spots on the dual tracks. The tracking servo corrects spindle motor runout and disk mounting eccentricity, maintaining a constant read envelope from the preformatted track signaling.

3.6.3.3 Stage Controller

The Stage Controller is a microprocessor based servo controller that drives and interfaces the translation stage access mechanism in the DDU. The translation stage acts as a coarse positioning actuator for the optical head. It serves two functions: coarse stage access and constant slew mode. Feedback is provided by a linear encoder and high level control is provided via the S/TODS Controller.

3.6.3.4 Spindle Controller

The Spindle Controller regulates the speed of the brushless DC spindle motor. It contains the spindle servo, commutation and control electronics and a three phase Pulse Width Modulated (PWM) trans-

conductance amplifier. The spindle servo receives a reference frequency from the DCS and locks it to the feedback signal of the optical encoder mounted on the shaft of the spindle. The particular rotational rate is determined by the radial position of the optical head, as described in the S/TODS BCAV format. The servo provides the analog error signal to the PWM amplifier and the motor Hall effect switches provide signals for proper commutation. The servo also provides maximum acceleration and deceleration torque to rapidly change the rotational speed when moving across bands.

3.6.3.5 DDU I/O

This module is responsible for handling various DDU control and monitoring functions. These include the media loader control and status reporting, magnetic bias device control, user panel interface, vacuum subsystem operation and requisite environmental regulation and monitoring.

3.6.3.6 Read Channel Processor

The Read Channel Processor (RCP) module receives the analog signals from each read data channel off the disk. The RCP Block Diagram is Fig. 3.6.3.6–1.

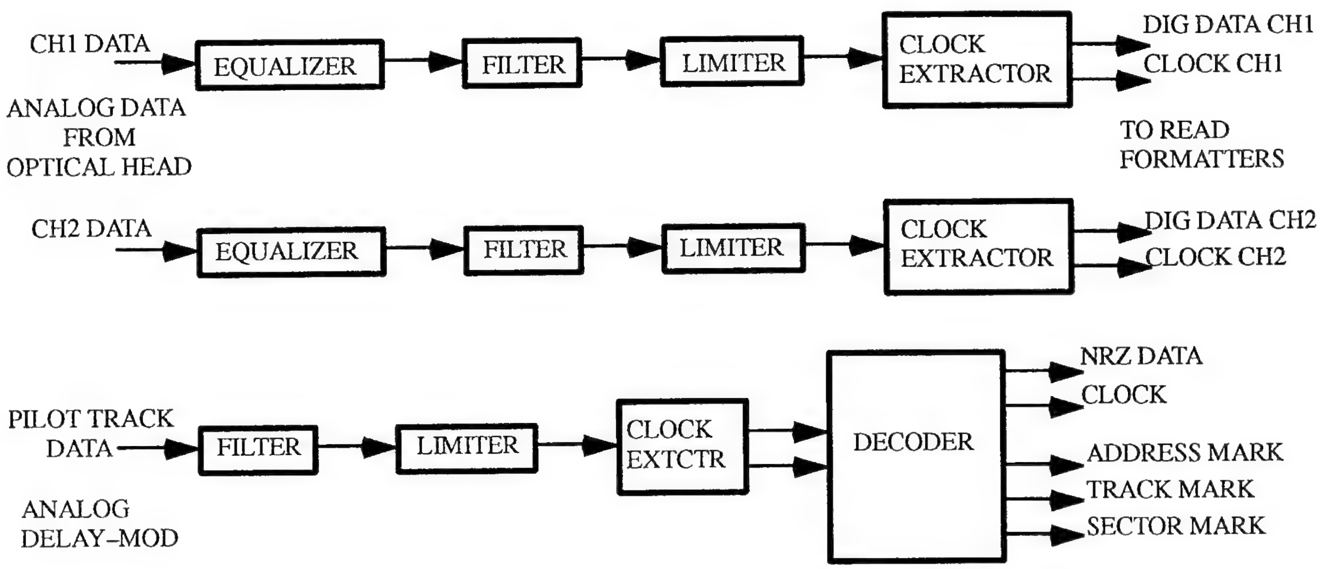


Fig. 3.6.3.6–1, Read Channel Processor Block Diagram.

The RCP first applies equalization to boost high frequencies to compensate for losses in the write/read channel. Next it provides filtering to remove high end noise. Then it limits (digitizes) the data. and performs clock extraction from the encoded data using an AFC controlled PLL circuit. The AFC loop in each PLL keeps the VCO near the desired clock frequency and thus minimizes the time to lock onto the incoming encoded data stream's clock information. Finally, it restrobes the data and sends it and the extracted clock to the Read Formatters. For the pilot track data, the decoder is also resident on the RCP board.

3.6.4 S/TODS FIRMWARE

The S/TODS firmware controls all disk operations and the SCSI interface based on commands received from the user. The user communicates with the S/TODS through the SCSI interface. The user

can perform a Built–In–Test by pressing a button on the S/TODS Front Panel or by selection from the host computer.

The S/TODS Firmware is composed of two Computer Software Configuration Items (CSCIs). The first S/TODS CSCI is the System Controller that controls all disk operations. The second S/TODS CSCI is the SCSI Adapter CSCI. This item provides a user command and data interface over a SCSI interface.

3.6.4.1 System Controller Functionality

The System Controller (SC) has control through Software of the System Functionality. The functions for which it is responsible are:

- Writing to the Optical Disk
- Read from the Optical Disk
- Erasing the Optical Disk
- Certifying the Optical Disk
- Performing self test with GO/NO GO indication
- Loading a Disk
- Unloading a Disk
- Front panel control
- Support of Maintenance Terminal commands
- Temperature and humidity monitoring
- Handle EU and DDU Interrupts

The Software for these tasks resides in the SC hardware. The SC hardware is shown in Fig. 3.6.4.1–1.

The SC includes in its hardware the Motorola 68020 processor, EPROM and RAM memories, the Hardware Timer and VME and DUART ports.

3.6.4.2 SCSI Adapter Functionality

The SCSI Adapter has control through Software of the System Functionality. The functions for which it is responsible are:

- SCSI standard computer interface

- Accepting SCSI commands, messages and user data according to ANSI X3.131–1986 SCSI Standard

All SCSI commands necessary for S/TODS operation have been identified. The S/TODS Firmware Operations discussion describes how each of the SCSI commands are used to operate the S/TODS.

The functions of the SCSI Adapter CSCI are:

- Receiving SCSI commands from the user
- Performing data transfer for read and write operations
- Passing Optical Memory and Direct Access commands to the System Controller CSCI
- Sending command status back to the user

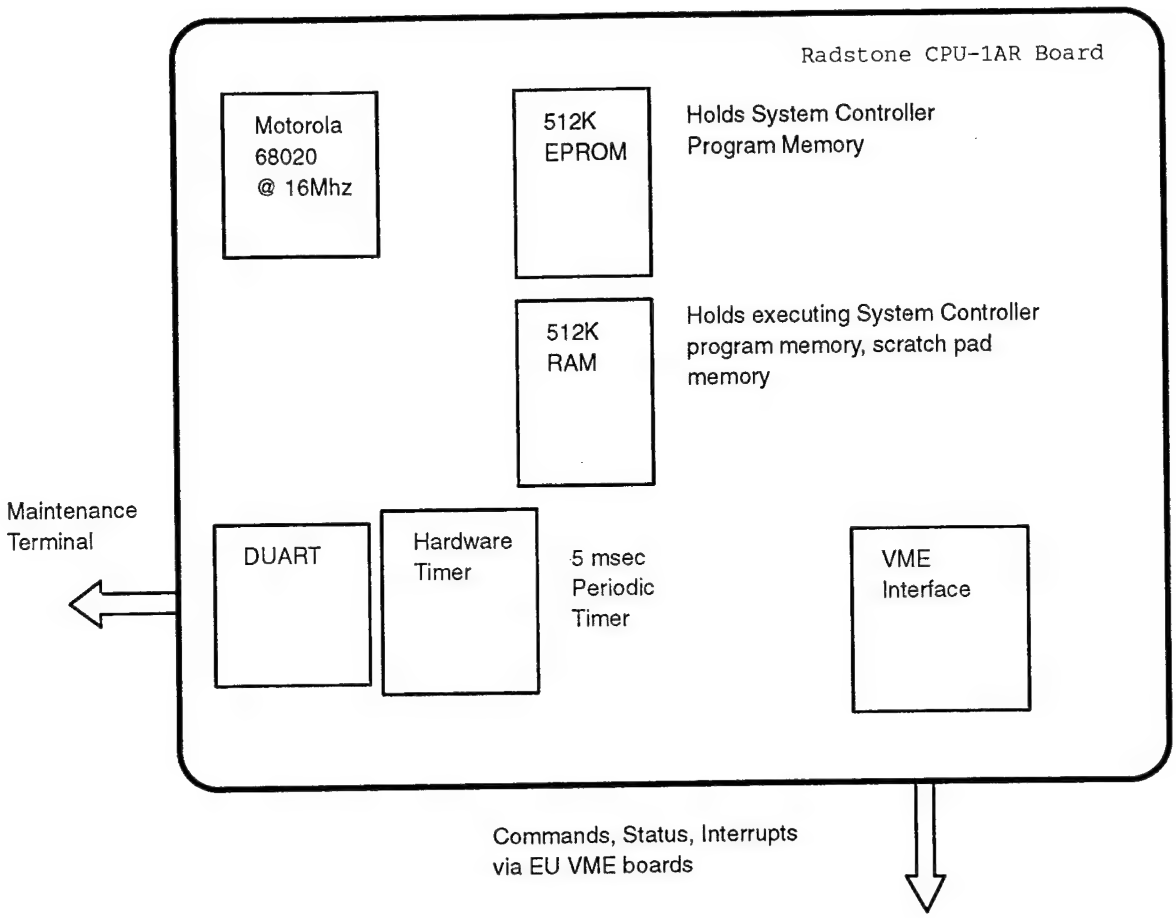


Fig. 3.6.4.1–1 , System Controller Hardware Block Diagram

3.6.4.3 S/TODS System Controller Architecture

The S/TODS System Controller Architecture is based upon design of individual modules. Each module controls a particular function or group of functions in the S/TODS unit. The modules are listed in Fig. 3.6.4.3–1.

The lower level architecture of the system is such that Optical Disk Operations, (Write, Read, Erase and Certify) are driven by interrupts from within the S/TODS unit. Flow control is handled by Track Buffer Overflow, Flow Control, and Empty interrupts. Tracking and control are driven by DCS Track Mark, Sector Mark and Pilot Track addresses. Data Sector Processing is driven by DCS Mid Sector and Sector End interrupts

Other interrupt driven operations are the maintenance terminal Support, where a user input causes an interrupt and the Laser Temperature Exceeded. These interrupts may be inhibited to allow a disk operation to be completed.

Polling, where a particular element is asked to report status, is used to support Loading/Unloading of Disks, the Front Panel and monitoring of Air Temperature, Spindle Motor Temperature and Relative Humidity.

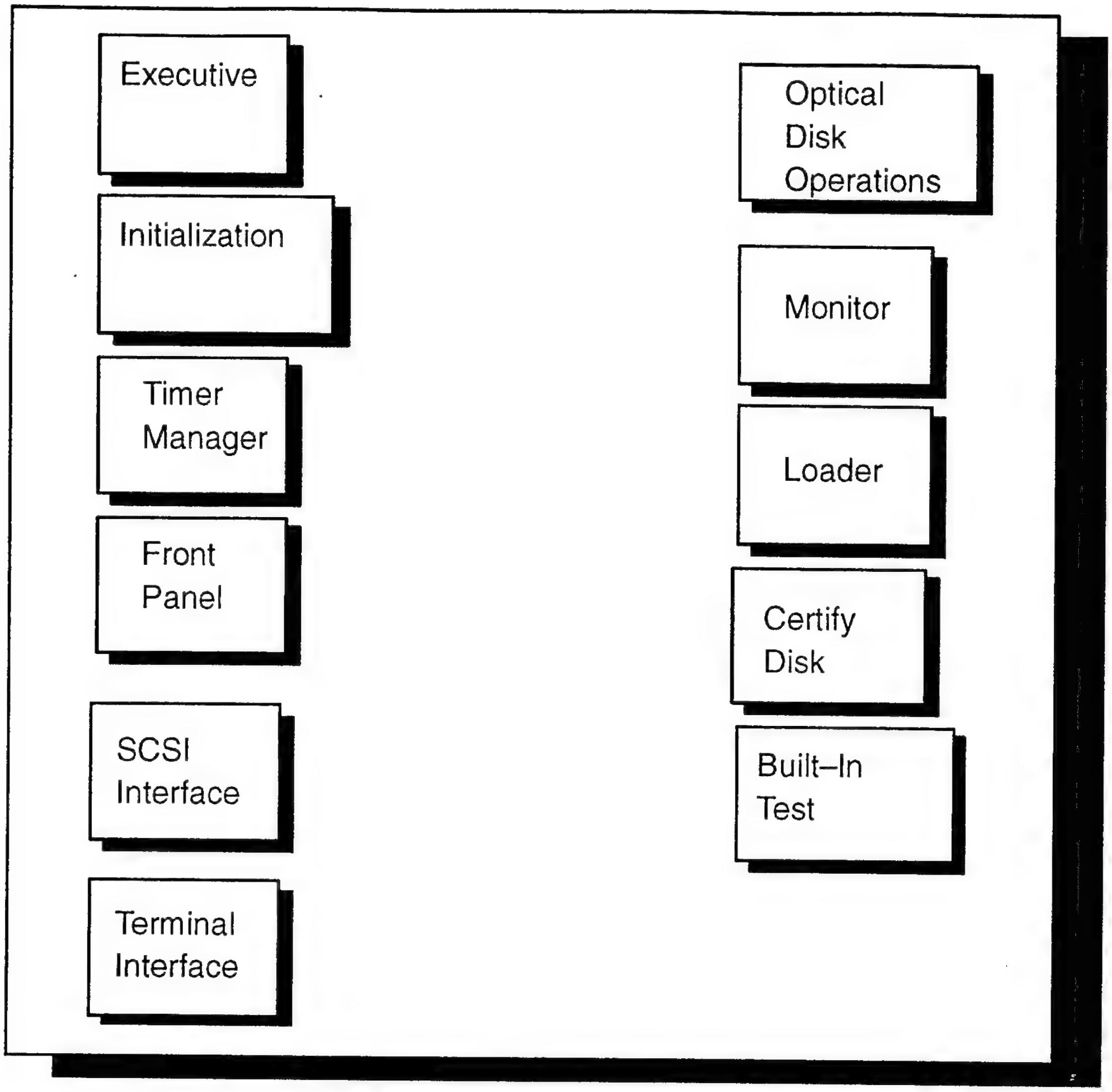


Fig. 3.6.4.3–1 , System Controller Architecture.

Communication between the Computer Software Components (CSC's) is via message passing. Each CSC has its own message queue. A message consists of 1. the action to be performed, 2. the source of the message and 3. additional information relevant to the action. One CSC may command action by another CSC by placing a message in that second CSC's message queue. Each CSC periodically checks its message queue at a maximum 50 msec. interval.

The System Controller Interrupt architecture consists of 7 interrupt levels. The priority ranks from 1 to 7 with 7 the highest. Level 7 interrupts are non–maskable. S/TODS interrupts that do not cause abortion of an operation are placed at level 2. S/TODS interrupts that cause abortion of an operation are placed at level 6. An AC power failure causes an interrupt at Level 7. Processing time for all interrupt routines do not exceed 100 microseconds processing time. This allows a maximum of 100 instructions to be processed.

In order to guarantee that interrupts are not passed to the user, most Write Read Operations are interrupt driven. Almost full interrupts in the Hardware FIFO initiate DMA transfers to Track Buffer

during Write operations. Almost Empty Interrupts in the Hardware FIFO initiate DMA transfers to Track Buffer during Read operations. In addition, the SCSI Controller has a Bus Service Interrupt to indicate complete data transfers, commands and messages. Polling is used to monitor the number of sector pairs processed during read operations.

3.6.4.4 S/TODS SCSI Architecture

The S/TODS SCSI Architecture is based upon design of individual modules. Each module controls a particular function or group of functions in the S/TODS unit. The modules are listed in Fig. 3.6.4.4–1.

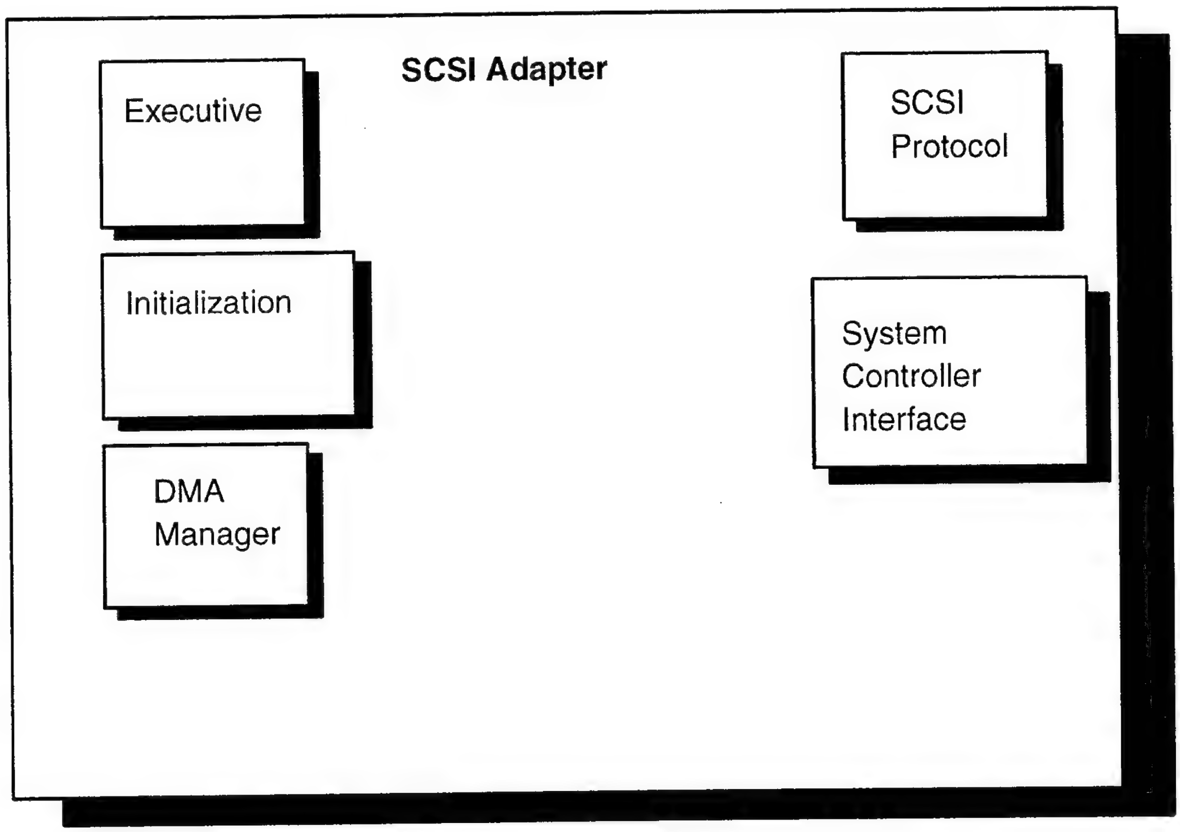


Fig. 3.6.4.4–1 , SCSI Adapter Architecture

In order to guarantee that interrupts are not passed to the user, the lower level SCSI architecture is structured so that most Write Read Operations are interrupt driven. Almost full interrupts in the Hardware FIFO initiate DMA transfers to Track Buffer during Write operations. Almost Empty Interrupts in the Hardware FIFO initiate DMA transfers to Track Buffer during Read operations. In addition, the SCSI Controller has a Bus Service Interrupt to indicate complete data transfers, commands and messages. Polling is used to monitor the number of sector pairs processed during read operations

3.6.4.5 Systems Operations Flow

The Flow of Systems Operations may best be understood by first examining the flow of commands for an operation, then the data flow and finally the flow through the SCSI interface. Also included

in this discussion are the Built in Test command flow and Self Test, both as operated from the Front Panel and from the Maintenance Terminal.

3.6.4.5.1 Read Logical Operations Flow

The Command flow for the Read Logical operation is shown in Fig. 3.6.4.5.1–1.

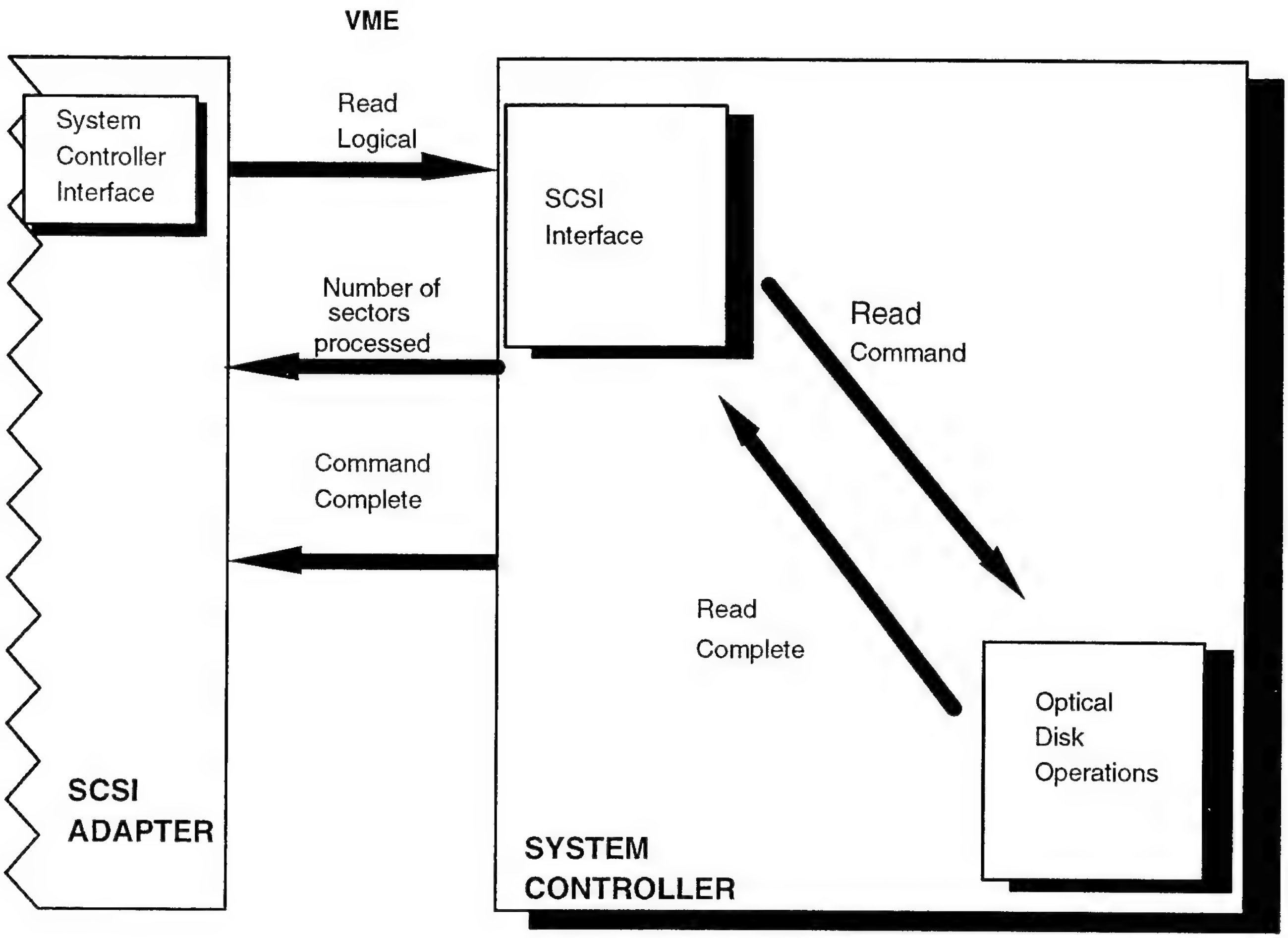


Fig. 3.6.4.5.1–1, Read Logical Command Flow.

To start the Read Logical (logical is the externally apparent address on the disk. Physical is the actual disk location. Logical must be converted to physical by a knowledge of PDL. All logical elements are addressable. Some physical elements are not addressable because they have been mapped out because of errors.) the command is passed over the VME bus from the SCSI adapter to the system controller. During the operation, the number of sectors processed continues to be reported to the SCSI adapter. At the end of the Read Logical operation, a Command Complete is sent from the SC to the SCSI adapter for transmittal to the host

The data flow for the Read Logical operation is illustrated in Fig. 3.6.4.5.1–2.

Under the control of the SC and the Host through the SCSI adapter, the Data flows from the track buffer over the VSB bus to the SCSI controller for transmittal to the host. Statuses are reported to

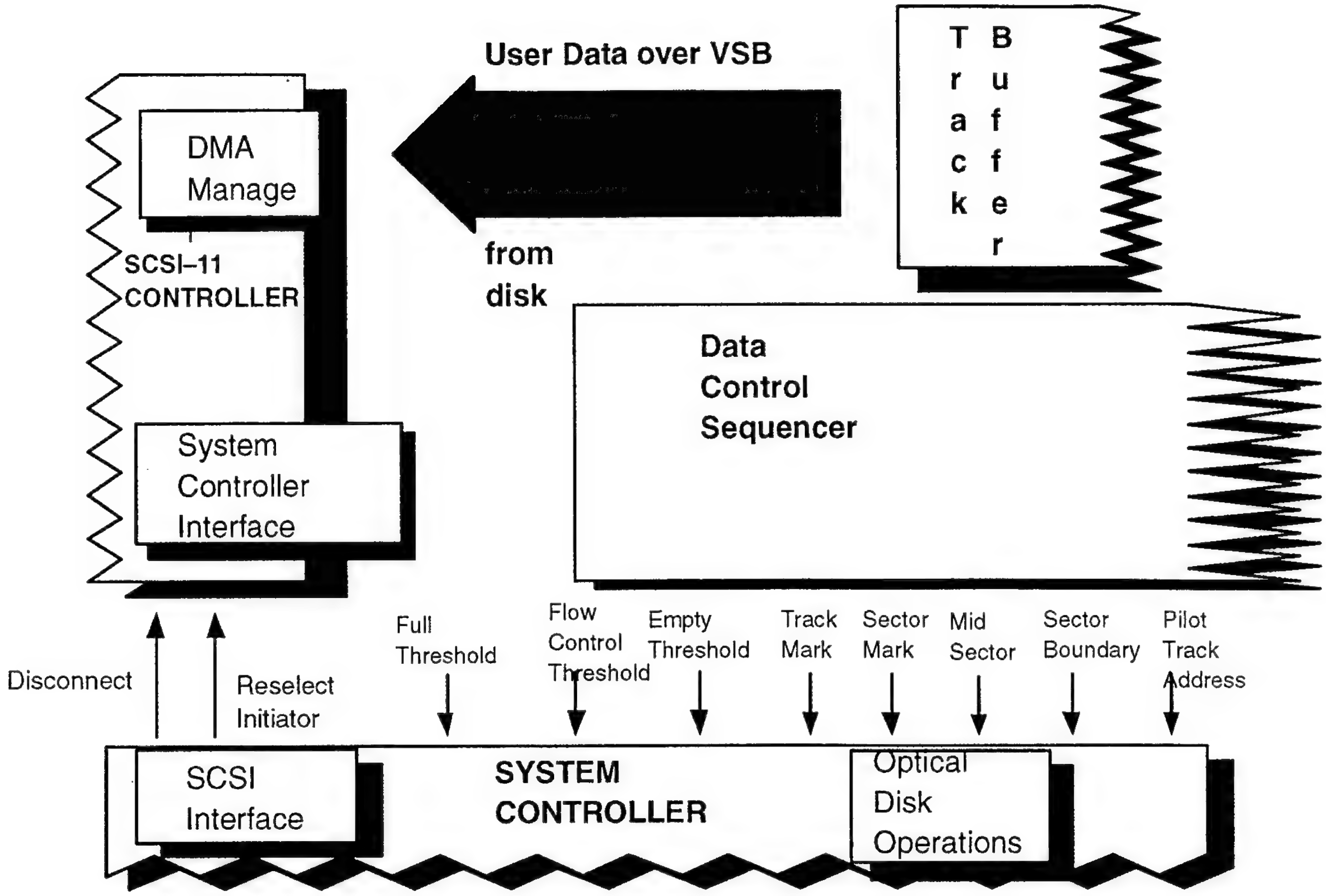


Fig. 3.6.4.5.1–2, Read Logical Data Flow.

the SC from the DCS. Three threshold statuses are used to inform the host as to the availability of data. Pilot track address is reported to allow access to the required data. Track mark, sector mark, mid sector and sector boundary are all needed to control data flow.

Figure 3.6.4.5.1–3 is a block diagram of SCSI Read Data Flow.

Read Data form the Track Buffer flows through the VSB interface into the FIFO as Direct Memory Accesses (DMA). It passes through the SCSI controller and onto the SCSI bus. When the FIFO is almost empty, an interrupt is passed to the board controller. The number of blocks processed is also passed to the SCSI board through the VME interface.

3.6.4.5.2 Write Logical Operations Flow

The Command flow for the Write Logical operation is shown in Fig. 3.6.4.5.2–1.

To start the Write Logical operation the command is passed over the VME bus from the SCSI adapter to the System Controller. At the end of the Write Logical operation, a Command Complete is sent from the SC to the SCSI adapter for transmittal to the host.

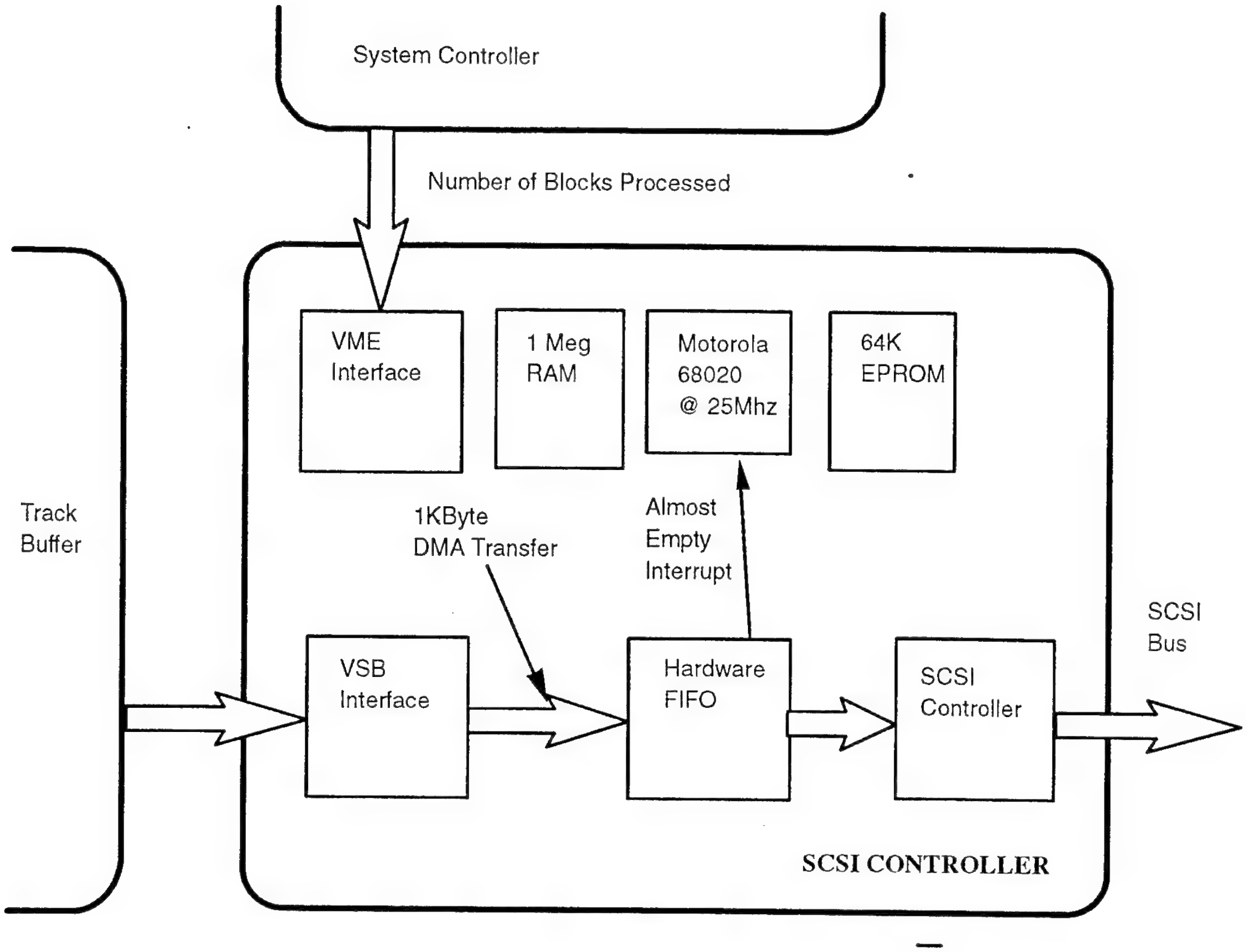


Fig. 3.6.4.5.1–3, SCSI Read Data Flow.

The data flow for the Write Logical operation is illustrated in Fig. 3.6.4.5.2–2.

Under the control of the SC and the Host through the SCSI adapter, the Data flows from the SCSI controller over the VSB bus to the track buffer for transmittal to the host. Statuses are reported to the SC from the DCS. Three threshold statuses are used to inform the host as to the availability of data. Pilot track address is reported to allow access to the required data. Track mark, sector mark, mid sector and sector boundary are all needed control data flow.

Write Data from the SCSI bus flows through the SCSI controller into the FIFO . It passes through the FIFO and into the VSB Interface as DMA and onto the Track Buffer. When the FIFO is almost empty, an interrupt is passed to the board controller. The number of blocks processed is also passed to the SCSI board through the VME interface.

3.6.4.5.3 Erase Command Flow

The Command flow for the Erase Logical operation is shown in Fig. 3.6.4.5.3–1.

To start the Erase Logical operation the command is passed over the VME bus from the SCSI adapter to the System Controller. During the Erase Operation the SCSI bus may be deselected at the request of the SC through the SCSI controller to allow the SCSI bus to support operations with other periph-

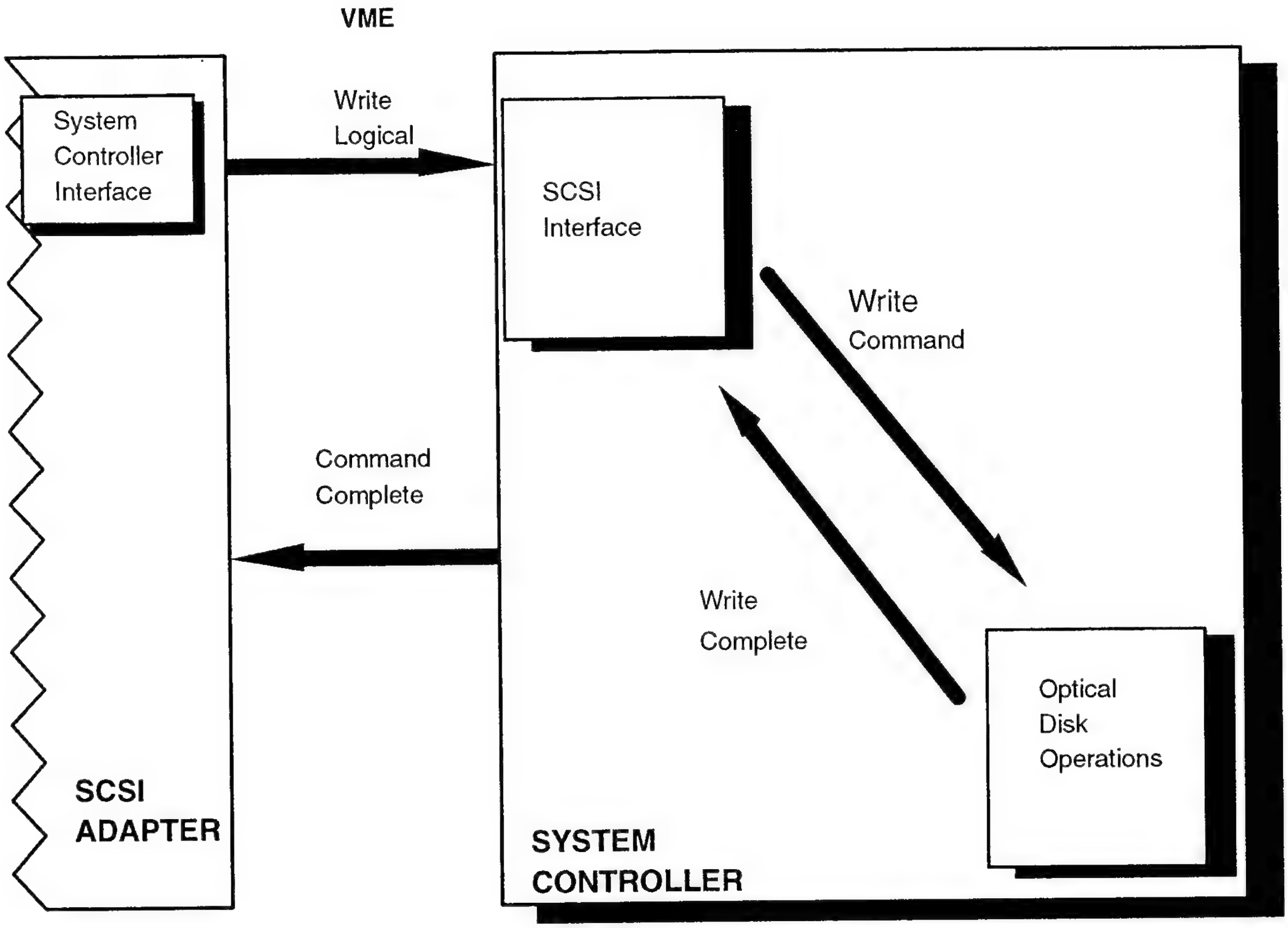


Fig. 3.6.4.5.2–1, Write Logical Command Flow.

erals. At the end of the Erase Logical operation a reselect is transmitted by the SCSI controller at the request of the SC. Upon reselection, a Command Complete is sent from the SC to the SCSI adapter for transmittal to the host.

3.6.4.5.4 Certify Disk Command Flow

The Command flow for the Certify Disk operation is shown in Fig. 3.6.4.5.4–1.

To start the Certify Disk operation the command is passed over the VME bus from the SCSI adapter to the System Controller. During the Certify Disk Operation the SCSI bus may be deselected at the request of the SC through the SCSI controller to allow the SCSI bus to support operations with other peripherals. At the end of the Certify Disk operation a reselect is transmitted by the SCSI controller at the request of the SC. Upon reselection, a Command Complete is sent from the SC to the SCSI adapter for transmittal to the host.

3.6.4.5.5 Built in Test Command Flow

The Command flow for Built in Test operations is shown in Fig. 3.6.4.5.5–1.

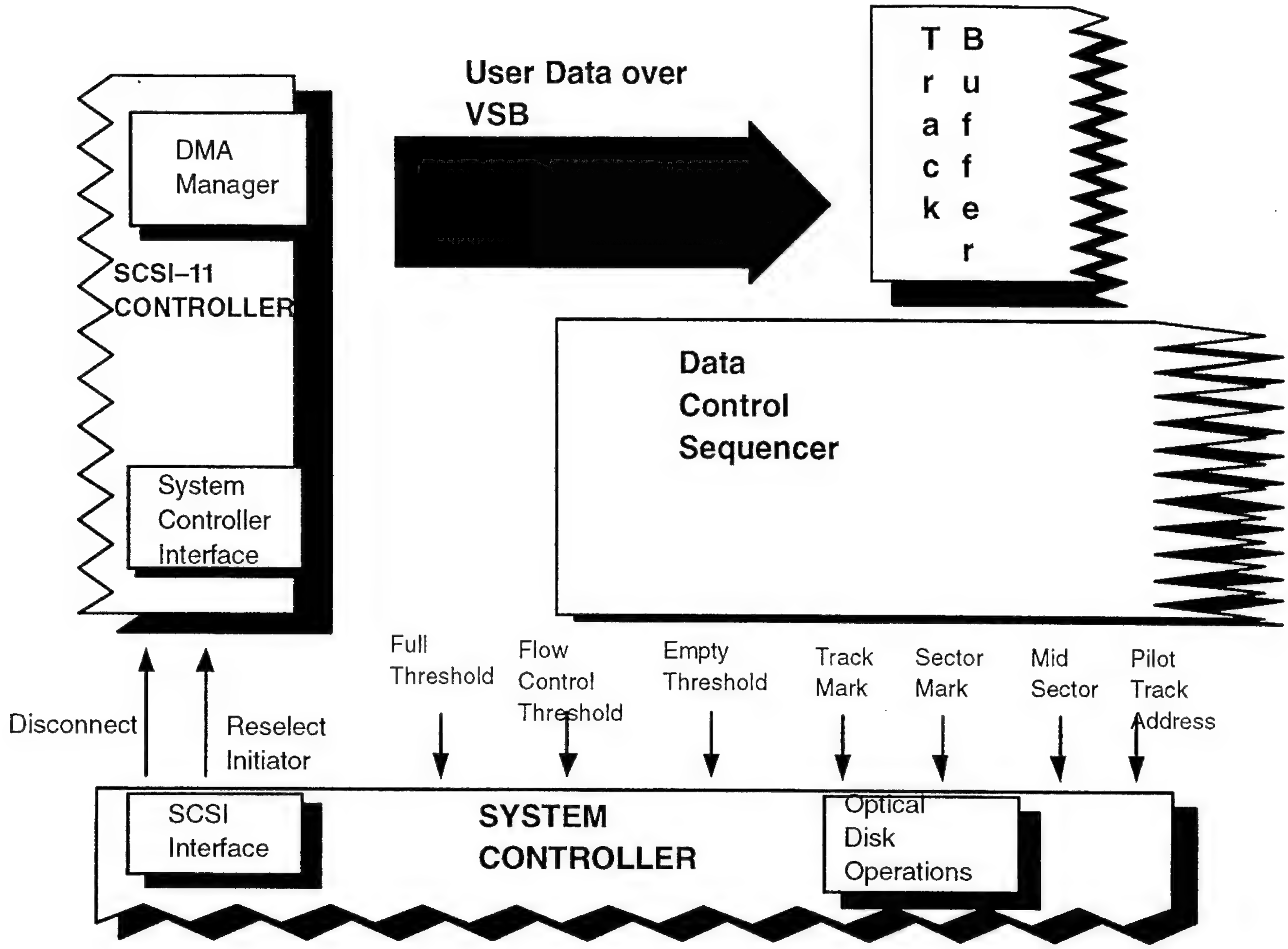


Fig. 3.6.4.5.2–2, Write Logical Data Flow.

To start the Built in Test operation the command is initiated by pressing the Test Button on the DDU. This operation. labeled (1) starts a sequence of (2) Erase, (3) Write and (4) Read operations at a preset Physical location on the Disk. The (5) Status is reported on the Front Panel by red indicating fail or green indicating pass LED indicators.

3.6.4.5.6 SCSI Commands

Control is implemented using the SCSI mandatory commands. The Direct Access and Optical Memory device models for SCSI are supported. The ANSI Standard for SCSI (American National Standard X3.131–199x) fully describes the SCSI interface and device models. This set of commands allows total operational control by the user.

Using the SCSI interface, the user is able to read and/or write data to that disk, re–certify the disk, erase data on the disk, unload a disk from the S/TODS, write a disk label on a loaded disk, and get the disk configuration. The SCSI Interface is controlled by the SCSI Adapter CSCI located on the SCSI II board of the S/TODS.

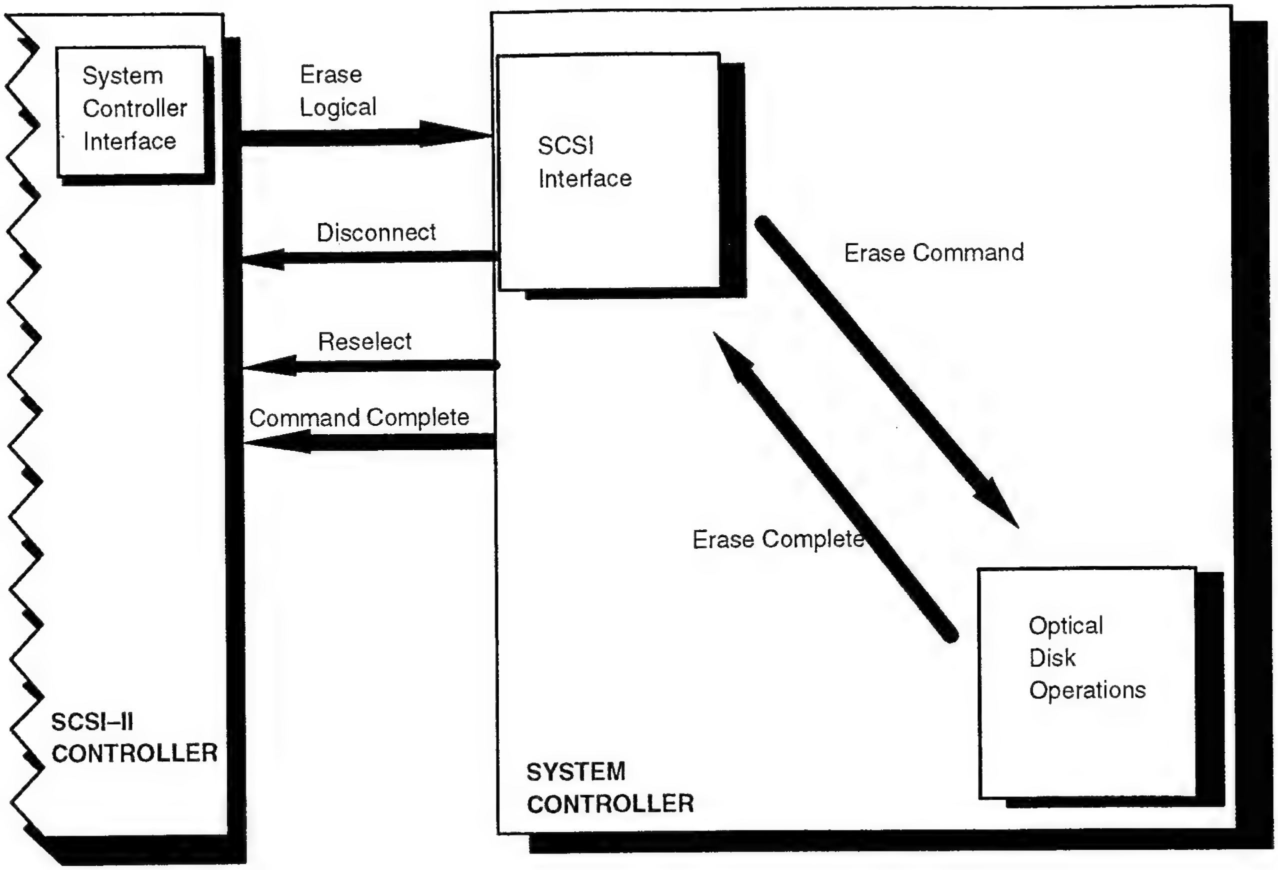


Fig. 3.6.4.5.3–1, Erase Logical Command Flow.

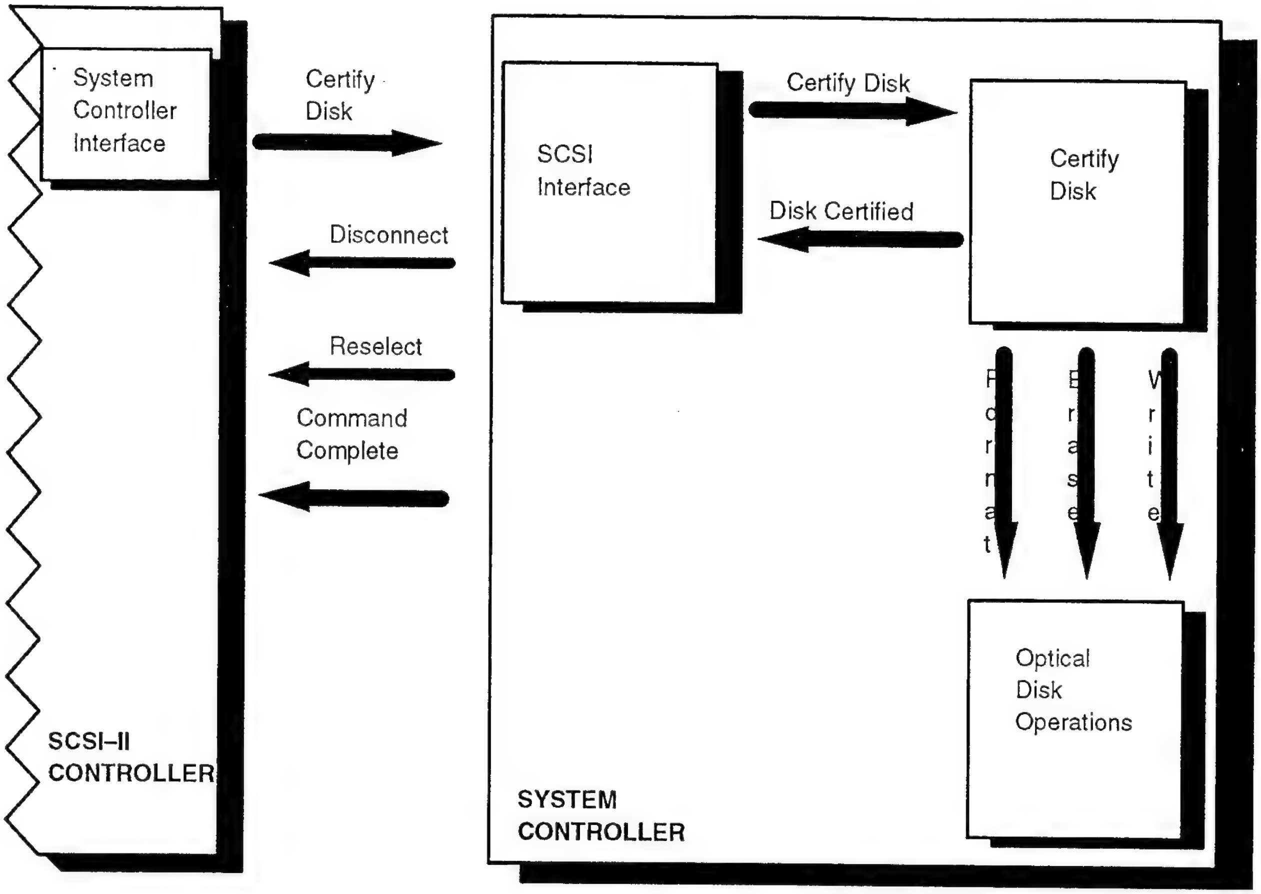


Fig. 3.6.4.5.4–1, Certify Disk Command Flow.

Command Interface For Self Test

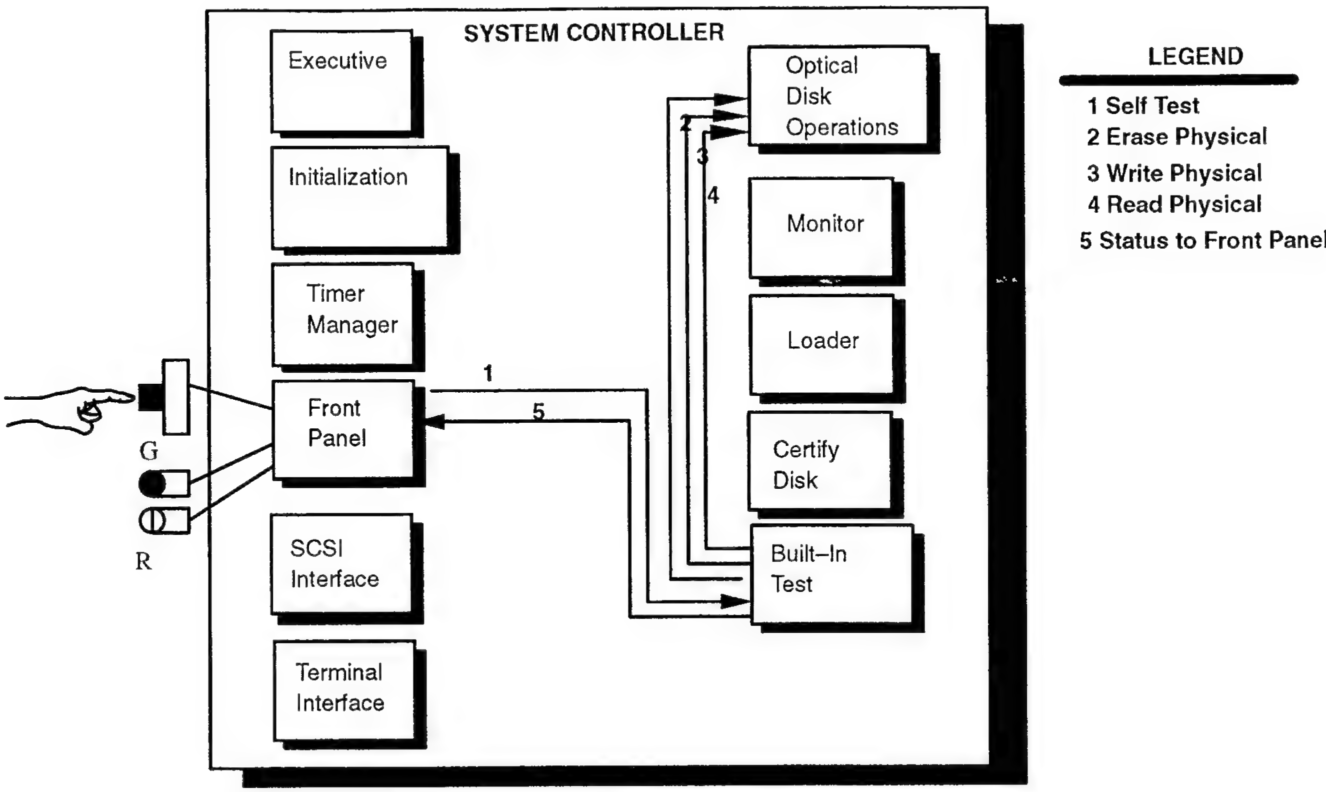


Fig. 3.6.4.5.5–1, Built In Test Command Flow.

SECTION 4

ADM PERFORMANCE RESULTS

4.1 INTRODUCTION

S/TODS underwent extensive testing in the laboratory during the integration phase of the program. Test data were accumulated in 23 standard RCA Corporation bound laboratory notebooks. The data recorded in these notebooks includes:

1. Recording Channel Analog Characteristics (Freq. Resp., SNR, Eye Pattern Quality, Ease of Tracking)
2. Recording Channel Digital Performance (BER, Capacity,)
3. Recording Media Characteristics (Laser Power Rqmnts., Eccentricity, Defect Distribution)
4. Servo System Performance (Focus System Bandwidth and Accuracy, Tracking System Bandwidth and Accuracy)

These notebooks are being preserved and the last updated. The following is a summary report of analog channel performance.

4.2 ANALOG CHANNEL PERFORMANCE

Because of the highly deterministic nature of the digital channel electronics, BER in the Analog Channel will determine the BER of the system. Channel margins have been examined for each of the two channels. Because the record side of the system incorporates the limiting action of the thresholding of the recording, the record side nonlinearities are dominated by the thermal conductivities of the disk. This results in a "teardropping" of the spot with the narrow end of the mark at the entry end. If the teardropping is compensated, the transfer function of the record side of the system becomes unitary out to some limiting frequency.

In this case, the read play characteristics dominate the channel performance. The channel performance has been evaluated on a per channel basis. The goal of this was to ensure that the performance of the channel is media defect limited.

Two differences between the channels were found: the write light intensity rising edge on Channel 1 was a few percent worse and a coma patch spot distortion on the read laser spot of channel 1. The coma seen in play spot 1 appears to be contributed by a "roll" or similar effect near the edge of the beam combining mirror. Although the beams are quite small (a few hundred μm in dia.) the beam for channel 1 lies within a few hundred μm of the mirror edge.

The rising edge problem is a write driver issue and is felt to be a minimal contributor. The coma patch, trailing the spot in the along track direction, does cause significant intersymbol interference. In addition, three factors degraded performance on both channels: write mark "teardrop" distortion, write power servo laser power offset, and a mark length variation versus feature size phenomenon. These three issues have always been present but did not affect Raw BER performance when system was optimized.

The read channel 1 coma distortion degrades performance, however, it can be tolerated with improved system performance. Correcting the coma requires opening the optical head and realigning it on the test fixture setup. It was decided to investigate and reduce or eliminate the other degradation factors affecting both channels. If acceptable margin is obtained the read spot distortion can be tolerated.

The write power offset issue produces a slightly under–recorded data waveform, where the negative data edges arrive earlier than the positive edges (all mark lengths are generally too short). This increases the raw BER by cutting into the clock to data edge margin, and by lowering the SNR due to producing slightly thinner written features. An external breadboard circuit was setup on Channel 1 to shrink the data feedback signal to the Write Power Servo, allowing a very accurate fine tune of the resulting servo locked write power. This adjustment capability significantly improved edge jitter and raw BER. The additional circuit was implemented with one additional IC on the RCP module, and has been installed permanently in both channels.

The teardrop distortion problem is an MO recording phenomenon where the written feature starts out narrow, then widens along its length producing a teardrop shape. Preheating by the leading edge of the gaussian write spot and by conduction cause the widening. This does not occur in the beginning of the mark, as the write laser is off when its leading tail is on the beginning of the area where the mark will be written. The read process sees this as a lower slope rising edge as compared to the falling edge resulting in second harmonic distortion. Also, the faster falling edge shows up as less clock to data edge jitter, yielding better data recovery. A circuit which compensates for this effect by writing the first part of the mark at a higher power was implemented on Channel 1, and shown to decrease the rising edge jitter and improve the raw BER. This circuit has been implemented on both channels.

The mark length variation is also under investigation. The cause of the variation has been narrowed down to the data detector/preamp, the equalization or the disk media/spot interaction processes with the media/spot interface the likely cause. The variation can be tolerated, though reducing it would improve performance. Write compensation previously determined to be not required, would reduce the variation. A write compensation circuit will not be implemented at this time.

The raw BER was resolved with the permanent installation on both channels of write power servo offset circuits and teardrop compensation circuits. The lower data edge jitter obtained brought the system performance to the desired media defect limited case, where the raw bit error rate is driven by the media induced errors. The system runs at 1 X 10 E–5 raw BER regardless of minimum feature size (across Bands), showing it to be media limited. The optical write spot coma and the mark length variation issues remain, though they are not strong enough performance degradations on their own to show in the raw BER and do not prevent error–free operation.

With the improved write operation the drive was shown to run with 0 errors; single Band (1 GB) BER tests were run in both the inner and outer Bands with no errors. The witnessed BER demo test was then run and passed, where the Flight Test erase/write/read operation is performed continuously over an entire 6 GByte disk side with 0 errors.

SECTION 5

SYSTEM TEST RESULTS

5.1 INTRODUCTION

The S/TODS Drive was extensively tested for performance and environmental effects on operation. This section covers Environmental Test and Flight Test.

5.2 ENVIRONMENTAL TESTING

Environmental tests of shock/vibration and temperature were conducted in four phases. Areas requiring improvement were identified and modifications to various areas of the Drive made. In each subsequent phase more extensive testing was performed. Results of the final phase, conducted as part of Acceptance Test, are discussed here.

Disk operations were performed without bit errors over a temperature range of –20 through +40 deg C. 15g shock was survived in all axies. 2g sine vibration from 5 Hz to 2 KHz was operated through with the exception of loss of track lock from 365 to 395 Hz, and loss of focus lock in the z axis only at 790 Hz.

5.2.1 SHOCK/VIBRATION

The S/TODS DDU and EU underwent 15g shock testing, 2g sine vibration, and a random vibration profile based on a C–141 environment.

5.2.1.1 Shock

The EU and the DDU were separately shocked 3 times at 15g, 11 ms duration, in the + and – directions for the x, y, and z axies. The non–tested unit was positioned on a cart next to the shaker, cabled to the tested unit. The system was powered up and operating in Standby mode; focused on a spinning disk during the shocks. Self Test was run before and after each set of 3 shocks, for a total of 18 shocks at 15g for each unit. The translation stage was in Band A at the PDL area, near the disk inner radius, where it is left after a disk load, with the disk spinning at Band A speed (max speed).

DDU shock in the z axis (focus direction) in both the + and – directions caused only a small spike in the focus error signal about two times the normal ambient level; not a problem even if a read/write operation had been in progress (this is not a system requirement). Y axis shock produced no noticeable effect. X axis – direction shocks produced no effect on the focus signal, however the X axis + direction shocks caused large error spikes on two of the shocks and loss of focus lock on the third. After reloading the disk Self Test was run and passed; loss of focus is not considered a failure for this test.

EU shock in three axes, both directions, was survived with a successful Self Test after each set. The system was operating in Standby mode as was done for the DDU shocks.

5.2.1.2 Vibration

Vibration testing of the DDU and EU (individually) was performed with the system exercising the Flight Test disk operation sequence of repeated Erase, Write, and Read sessions. Sine 2g (spec) tests

were run as well as reduced amplitude 1g and 0.5g investigative tests. Also a weighted random vibration curve was run, based on a published C–141 environment with a 50 Hz isolated rack. The EU passed all three axes, the DDU had a tracking problem operating through both the sine and the random tests.

The EU passed for the x and z axes 2g runs, and operated through the y axis 2g test however the front panel welds to the chassis were broken off. The unit did not come out of the fixture; it remained captured between the front panel rack attachment and the rear taper pin mounts. The spot welds (designed/constructed by the EU chassis subcontractor) were unable to take the force required, so the panel was drilled and through–bolted to the chassis. The y axis 2g sine test was then rerun with no problems; there was no other damage to the unit.

The DDU under vibration showed a broad area of 200 to 750 Hz where the system was unable to track, being repeatedly knocked off the pilot. The problem occurred in all three axis with some variation in problem frequency. At low frequency, below 100 Hz, there was no problem with tracking, even below the resonance of the internal isolators (10 Hz). This area had been a problem in earlier vibration testing and had been solved by increased DC gain in the tracking servo loop.

With the DDU cover removed, some investigative work was done searching for internal resonances in the 200 to 750 Hz range with accelerometers. A number of fairly low Q resonance motions were found and reduced with damping materials, and transmission through the cabling was reduced by going to a larger number of smaller bundles in the service loops and adding foam isolation. It was shown that the internal DDU isolators performed as designed, giving at least 10:1 reduction in acceleration above their 10 Hz resonance. The areas suspected to be resonance problems included the cantilevered stage motor, the rear casting wall, the vacuum tank, and the optical head electronics board on it's post mounts. A number of vibration peaks in the problem range remained; due to the mechanical complexity finding and eliminating all of them would require more expensive shaker time than scheduled. Because the remaining vibration peaks were fairly low amplitude it was decided to address the problem with servo modifications (see below).

5.2.2 OPERATING TEMPERATURE

Operating temperature tests were conducted over the specified range of –40 degree C to +46 degree C. Erase, write, and read operations were performed over the range in 10 degree increments, after allowing the units to settle at each temperature. No data errors occurred over the range –20 deg C to + 40 deg C. This range is sufficient for the typical airborne installation, and is used as the published operating temperature range.

User data bit errors were detected in the –30 deg and +46 deg tests; a –40 deg test was not conducted. The cause of the errors was not investigated due to time limitations in the environmental test facility and the difficulty of sufficiently instrumenting the Drive while in the temperature chamber. The errors at the high temperature are suspected to have occurred through temperature induced temporary misalignment of the read and write beams. No permanent misalignment occurred, and after return to room temperature the Drive operated fine.

At the low temperature, the errors are believed to occur due to inappropriate write laser power. The algorithm used to set the initial power is based on laser temperature and disk radius only. The laser temperature is maintained at 0 deg C by the optical head heater when ambient goes below 0. The theory here is the disk requires a different initial write current at –30 deg than at 0 deg, and the setting used for the test was to far away from the required value for the write power servo to lock and get

to the correct laser current. This could be handled by adding a disk temperature sensor and including this information in the laser current algorithm, likely allowing operation down to –40 deg C.

5.2.2 NON–OP TEMPERATURE/TEMPERATURE SHOCK

Non–op temperature testing was conducted with the drive power off from –57 deg C to + 77 deg C, including 6 hours soak at the extremes and full transition temperature shock at 3 deg/min. Following the test the drive initialized and loaded, but had bit errors on new recordings. Read only testing of old recordings showed no bit errors and on other operational problems.

The cause to the write problem was found to be a read–while–write optical misalignment, were the read laser spots were not following the written tracks. The mirror in the optical head used for this alignment moved due to it's steel adjustment screw pulling on the aluminum mount under differential temperature contraction. After resetting the adjustment, the screw was locked in the center of it's backlash range and the mirror locked in place to avoid future problems. Calculations showed the backlash range to be sufficient over the –57 to +77 deg C range to avoid contact with the mirror.

5.3 FLIGHT TEST RESULTS REPORT

5.3.1 INTRODUCTION

The results of tests performed on the Strategic/Tactical Optical Disk System (S/TODS) are presented in this report.

During September 1993 the system was installed and tested on RC–135B aircraft serial number 61–2666, at the E–Systems Greenville, Texas facility. The recorder demonstrated successful operation under stressful flight tests conditions. The disk drive operated without error through aircraft maneuvers including 60 degree bank turns, takeoffs and landings, and tactical descents.

5.3.2 TEST ARTICLE DESCRIPTION

5.3.2.1 S/TODS System

The S/TODS system is a 12 GB optical disk drive consisting of a Disk Drive Unit (DDU) and Electronics Unit (EU) and is designed to interface with a computer using a SCSI interface. The flight test configuration included a rack mounted flight test computer which provided the control and data for the disk drive.

A PC laptop and GRiD computer were also used as terminal emulators. The laptop interfaced with the flight test computer for controlling and monitoring the test progress; the GRiD, supplied by Det 2, was used for monitoring EU internal status.

S/TODS interface to the aircraft consisted of two power sources. 115 VAC 400 Hz supplied the EU. 115 VAC 60 Hz supplied the flight test computer, the two laptop computers, and a vacuum pump in the DDU. The DDU received its operating power directly from the EU. Normally the DDU vacuum pump would be powered from a power converter internal to the DDU. However, this converter was inoperative when the unit was shipped to Greenville so a small amount of 115 VAC 60 Hz was required for the DDU.

The entire system with the exception of the laptop computer was installed in a short, two bay 19 inch rack installed in the left side aft area of the aircraft across from the aft right side door. The laptop was held by the test personnel during flight.

5.3.2.2 Operation

The S/TODS system uses a removable 14 inch optical disk. The disk may be written on both sides, however, it must be manually turned over. Loading a disk consists of inserting the disk cartridge into the slot on the front of the DDU until the built–in motor pulls the cartridge into the unit. The disk is automatically extracted from the cartridge and the empty cartridge is ejected from the DDU. Once the cartridge is extracted by the operator, the DDU lowers the disk onto the spindle and spins up the disk to operating speed.

A disk is removed using the reverse of the insertion procedure. An eject button on the DDU is depressed. After the disk has spun down, the loader raises it and prompts the operator through an LED on the front panel, to insert the empty cartridge. The cartridge is pulled into the unit and is ejected with the disk reinserted.

A self test function is provided. Self test is activated by pressing the labeled button on the DDU. Self test operates on a portion of the disk that is reserved for system use. It performs a megabyte write followed by a read and bit error check. Self test returns a non–ambiguous GO/NO GO LED indication.

The flight test computer provides a more comprehensive read/write test of the disk. The operator may select the starting location on the disk following which, the test will write pseudo random bit patterns on the disk, then read them back and check for bit errors. For each 50 blocks of data tested, a screen of statistics is provided detailing the number of corrected bit errors, uncorrected bit errors, and uncorrected bit error rate (BER). Additional statistics concerning system operation such as laser read and write current and rewrite counts are also displayed. All data may be logged for post flight analysis.

The GRiD computer is connected directly to the EU and allows low level monitoring and control of various test points and status words. The GRiD is primarily a debugging tool and in normal operation is not used.

5.3.3 TEST DISCUSSION AND RESULTS

Three categories of tests were performed on the S/TODS system. Initial system tests verified operation of the equipment upon arrival in Greenville before installation in the aircraft. Ground tests verified operation after aircraft installation. Flight tests demonstrated error–free operation in the RC–135 environment.

Data sheets and flight notes taken during flight test were recorded in Lab Notebooks and are preserved. Each phase of testing is summarized below.

5.3.3.1 Initial Tests

Initial tests were performed to ensure no damage to the system was sustained in shipment from Martin Marietta to E–Systems. The system was set up on a bench in the Materials and Processes (M&P)

lab in Building 153 and connected to lab power. Because no 400 Hz power was available in this lab 60 Hz was used to power the EU and DDU. Separate 60 Hz fans were required for cooling. Early tests were successful with no uncorrected bit errors or equipment failures.

A second set of initial tests were performed the next day. Problems were encountered during these tests with disk spindle motor control. On the theory that machinery in the lab was corrupting the power lines, the system was moved to an unused conference room in Bldg. 153. At this location, the problem persisted and upon further investigation, a failure in the spindle shaft encoder was determined to be the problem. Martin Marietta personnel corrected the problem by adjusting the encoder position. Further tests were successful.

5.3.3.2 Aircraft Ground Tests

Ground tests were performed after S/TODS installation on the aircraft to verify the installation and verify readiness prior to first flight. The system powered up correctly and performed the flight test routines with no uncorrected bit errors or equipment failures and was determined to be ready for flight test.

5.3.3.3 Flight Tests

Three flights were flown with the S/TODS system:

Flight	Date	Take Off	Land	Duration
1	17 Sep 93	1200	1602	04:02
2	20 Sep 93	0724	1042	03:18
3	21 Sep 93	1300	1541	02:41

Flight plans and objectives for each flight are contained in the S/TODS Flight Test Plan. This information is preserved in the Lab Notebooks.

Aircraft Nav data, recorded during flight is contained in the Lab Notebooks. Partial data was available for flight 1. No data was available for flight 2. Full data was available for flight 3.

Plots of Latitude vs. Longitude and Altitude vs. Time for flights 1 and 3 are also included in the Lab Notebooks.

5.3.3.3.1 Flight Test Operations

Flight test objectives were to demonstrate system performance in a RC–135B flight environment. the following system functions were evaluated:

1. Disk loading/unloading.
2. Disk speed control.
3. Read/write head positioning and focus.
4. Read/write performance, Bit Error Rate (BER).

The system was operated and tested in stable, level flight, ascent/descent, including tactical descent, and takeoff/landing.

5.3.3.3.2 Flight Test Results

All flights were successfully completed as planned with the exception of flight 2 on 20 Sept 93. On this flight, during airborne refueling, the disk loader failed to operate properly. Multiple attempts to load a disk were unsuccessful, resulting in an early termination of the flight. The failure was traced to a broken sensor wire at a connector on the loader mechanism.

During the three flights, a total of 7 Gbytes were written and read. Zero bit errors occurred.

Prior to flight 1, the system had problems initializing. The air inlet for the Electronics Unit was blocked off to allow the unit to warm up. Initialization proceeded normally afterward.

Prior to flight 2, during taxi, the disk spindle speed control would not lock. Tapping the spindle was required and was accomplished before takeoff. The same problem occurred during preflight for flight 3. This time, the spindle had to be hit harder to function.

After touch and go number 9 on flight 3, the spindle unlocked. The disk was reloaded and the system continued to function through the remainder of the flight.

Copies of notes taken by the Martin Marietta flight test crew are preserved in the Lab Notebooks. The flight test log is also contained in the Lab Notebooks.

5.3.4 CONCLUSION

The S/TODS system was successfully flight tested on RC–135B, S/N 61–2666. All the planned objectives were met and the system performed with zero bit errors detected in over 7 Gbytes of data written to the disks

APPENDIX A

LIST OF ACRONYMS

ADM	ADVANCED DEVELOPMENT MODEL
ANSI	AMERICAN NATIONAL STANDARDS INSTITUTE
ASIC	APPLICATION SPECIFIC INTEGRATED CIRCUIT
BER	BIT ERROR RATE
CLV	CONSTANT LINEAR VELOCITY
CNR	CARRIER–TO–NOISE RATIO
CRC	CYCLIC REDUNDANCY CODE
CSC	COMPUTER SOFTWARE COMPONENT
CSCI	COMPUTER SOFTWARE CONFIGURATION ITEM
DCS	DATA CONTROL SEQUENCER
DDU	DISK DRIVE UNIT
DMA	DIRECT MEMORY ACCESS
EDAC	ERROR DETECTION AND CORRECTION
EDM	ENGINEERING DEVELOPMENT MODEL
EPROM	ELECTRONICALLY PROGRAMMABLE READ ONLY MEMORY
EU	ELECTRONICS UNIT
FEM	FINITE ELEMENT MODEL
FIFO	FIRST IN FIRST OUT
FPGA	FIELD PROGRAMMABLE GATE ARRAY
FTA	FOCUS TRACK ACTIVATOR
FTL	FLIGHT TEST COMPUTER
FTS	FOCUS TRACK SERVO
LDA	LASER DIODE ARRAY
LED	LIGHT EMITTING DIODE
LSM	LASER SOURCE MODULE
LTSS	LINEAR TRANSLATION STAGE SYSTEM
MO	MAGNETO–OPTIC
MTBCF	MEAN TIME BETWEEN CRITICAL FAILURE

NA	NUMERICAL APERTURE
OHA	OPTICAL HEAD ASSEMBLY
OHE	OPTICAL HEAD ELECTRONICS
PDL	PRIMARY DEFECT LIST
PLL	PHASE LOCK LOOP
PPBS	PARTIALLY POLARIZING BEAN SPLITTER
PWM	PULSE WIDTH MODULATION
RAM	RANDOM ACCESS MEMORY
RCP	READ CHANNEL PROCESSOR
RWW	READ–WHILE–WRITE
SC	SYSTEM CONTROLLER
SCSI	SMALL COMPUTER SYSTEMS INTERFACE
SNR	SIGNAL–TO–NOISE RATIO
S/TODS	STRATEGIC TACTICAL OPTICAL DISK SYSTEM
TMO	THERMO MAGNETO–OPTIC
VCO	VOLTAGE CONTROLLED OSCILLATOR
WORM	WRITE ONCE READ MANY

APPENDIX B

OPTICAL DISK MEDIA

FOR TACTICAL DISC SYSTEM

FINAL REPORT

3M CORP.

OPTICAL DISC MEDIA
FOR TACTICAL DISC SYSTEM

Final Report

April, 1994

Author:
Dr. Robert F. Hellen

This report has been prepared under
Purchase Order Number 942969-0001-22-S22
with the
Martin Marietta Company
Camden, NJ 08102

3M
Rewritable Optical Laboratory/3M
Building 544
Vadnais Heights, MN 55110

CERTIFICATION OF TECHNICAL DATA CONFORMITY

The Subcontractor, 3M, hereby certifies that, according to the best of its knowledge and belief, the technical data delivered herewith under Purchase Order Number 942969-0001-22-S22 is complete, accurate and complies with all requirements of the contract.

Date: May 25, 1994

Robert F. Hellen

Robert F. Hellen
Technical Program Manager
(Certifying Official)

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REPORT INTRODUCTION

This is the final report prepared under Purchase Order Number 942969-0001-22-S22 with the Martin Marietta Aerospace Division. The program was designed to manufacture optical disc media for use in a ruggedized drive environment in a Tactical Optical Disc System (TODS) being designed and built by Martin Marietta. The intent of the program at its onset was to adapt 3M's existing commercial optical disc media manufacturing technology for the manufacture of 14" glass based optical disc media utilizing a Martin Marietta defined format. Since 3M's commercial media is designed around much smaller sized plastic media, there were some modifications required to achieve the desired end result. A lot of specialized equipment was used because of some of the unique elements in the manufacturing process relating to the size factor of the TODS media. Special disc carriers were also designed and built to enable the use of the production magneto-optical thin film coating system for the vacuum coating of the active optical thin film stack.

This is a summary report of the activities conducted on the various tasks as specified in the contract Statement of Work. The report details the various technical issues and problem areas that were encountered during the duration of the technical development program. The report will follow the actual process flow sequence as it occurred in the manufacture of the discs as opposed to following the task sequence as defined in the original Statement of Work. This was done to facilitate the technical discussion and to better present the various technical issues and problem areas as they occurred in the program sequence. Some of the main technical concerns that developed during the course of the program included the glass haze issue that resulted in photopolymer dewetting, the problems with the discontinuities in the 3M OD concentricity test band area and the general area of disc defects. The glass haze issue was a time dependent one and resulted in a quantity of glass being unusable due to the formation of the haze on the surface and the resultant photopolymer dewetting during the glass formatting phase of the process. The other main issue was that of defining an acceptable defect level on the final deliverable discs. This was primarily a result of the process flow used in the TODS disc preparation and the added cleanliness requirement that producing a 14" would require but that was not in the scope of the TODS research program. The report is broken down into sections corresponding to the specified tasks in the Statement of Work. For Task 5.0 which is Product Manufacture there is not a lengthy discussion of that specific activity in a separate section. Rather it is included in the other task sections as the Product Manufacture activity involved all of the other process steps.

There is also a general discussion on the subject of glass as it relates to its use in the manufacture of optical discs.

TASK 1.0 FORMATTING

This task as defined actually encompasses a number of different individual tasks or process steps which will be treated as such. These tasks include mastering, stamper preparation, glass formatting and the thin film deposition on the formatted glass.

Task 1.1 Mastering

This activity includes the cleaning and preparation of the 16" glass substrates, the photoresist coating of these substrates, the actual recording of the customer format pattern using the 3M Master Recorder and the development of the recorded masters.

For the glass preparation and photoresist coating the standard techniques that are used for video disc preparation were adapted for use to prepare the coated glass masters. The main issues of concern were the general overall cleanliness and the photoresist thickness since 16" glass masters were never coated before on the existing coating equipment. It was determined from the outset that defining the final groove geometry would be an iterative process. This was necessary because of some of the unique aspects of the TODS disc drive system optics and the fact that 3M did not possess a duplicate disc drive unit to do in house testing. A number of different groove geometries would have to be tried to arrive at the optimal geometry for the system optics in the TODS disc drive unit. This was necessary so that the required track crossing and push pull signals could be obtained for the drive unit to function properly. Otherwise 3M was to transfer the format information as provided by Martin Marietta and incorporate this into a formatted glass surface that contained all of the appropriate format information.

Several parameters in the mastering process were controllable that could be varied to arrive at different groove geometries. These included the photoresist thickness, laser power, beam spot size and profile as well as the development process for the recorded master. In the early stages of the program the plan was to record test masters that intentionally had an assortment of groove geometries that could then be evaluated by Martin Marietta on their disc drive test system. 3M was not set up to do an exact duplicate set of tests of what Martin Marietta was set up to do. 3M had in house capability to do testing for the track crossing and push pull signals but it would be with a system with different system optics. One of the main tests that 3M did was to make

Scanning Electron Micrographs (SEMs) of replicas made from the developed masters to check the groove geometry. 3M could also break up a glass master and do the same thing with these pieces. This served to give an in house measure of the reproducibility from one master recording to another as indicated by the SEMs of the groove geometry. The main test responses of concern were the track crossing signal and the push pull signals as these are the ultimate functional test response for the system optics and electronics. SEMs permitted quicker response time for trying to optimize the recording parameters. This became important because of the ongoing changes that were occurring with 3M's master recorder system and the need to be able to dial in the appropriate machine settings that would give the same groove geometry as was generated in the previous TODS recording.

In practice 3M would make up several pieces of photoresist coated 14" video disc master glass that were coated at the same time and with the same coating solution and conditions as the good pieces of 16" master glass. These 14" pieces of glass were not charged to the contract but were used to help establish the recording settings that would be used to record the good 16" glass. This is where breaking up the glass of the recorded, developed 14" masters for SEMs became important as this could be done in a very short period of time providing feedback for any minor changes that might be required on the recorder before recording the good 16" glass masters. This became very important because of all of the time demands on the recorder as this was used for recording commercial product masters as well and different settings were used for each product. In the master recording there are development test bands that are used to determine the end point for development and the resultant groove geometries. However, because of the difference in sizes between the smaller and larger master glass blanks this was not an exact science. It did serve as the final control on the groove geometry.

One issue that became a problem in the mastering for the final deliverable discs was the presence of what can best be described as missing information. Basically this was a small spot on the disc surface that was not completely developed and thereby contained no tracking or track ID information. What this resulted in for the formatted glass substrates was a smooth or land area on the surface of the master which contained no grooves or pits. If this area was small enough, then it would not have a major impact on the disc playability. If it was large then it could have a larger impact. Usually these areas were optically flat and did not serve to refract the beam. For the TODS final deliverable masters this was a small problem and varied with the master.

For the master glass itself there were a limited number of options when it came to identifying a suitable vendor for the 16" glass blanks as most vendors only made glass up to a 14" diameter size. Opton Inc. became the vendor for this contract because of their bid and their ability to provide the required 16" size. Inspection of some of their glass blanks prior to doing any coating at all indicated that some additional cleaning would be required before these could be used in our photoresist coating process.

MASTERING CHRONOLOGY:

For the first deliverable discs three test masters were recorded in November of 1990 that were used for the preparation of some 200 mm disc samples. For the three masters two were duplicates and were recorded with a 0.7 NA lense. The third master was recorded with a 0.8 NA system. One of the duplicate test masters cracked so only two of the three were used to make stampers. This permitted evaluation of two different groove geometries due to the difference in the NA of the recording system optics. Stampers were made from these masters and some 8" glass discs were replicated from these and then thin film coated. This size was chosen because of the availability of 8" blanks that 3M had in house that were used in another program. Because of the lack of availability of lamination equipment for 8" glass discs, the deliverable samples were sent to GE as single sided discs. This was done to quickly provide them samples for testing.

Discs made from these test masters were to be used by GE to help define the required groove geometry for the next recording iteration. The two masters used were Log numbers 2570 and 2571.

The next mastering iteration was done in August of 1992. For this iteration a full 14" format test master was generated which provided a number of different test bands that would permit GE to test over the whole specified read/write area of the disc. The format information was provided to 3M by Martin Marietta on a series of 5 1/4" magneto-optical discs that were then transferred to the mastering system electronics. The format definition for this was based in part of the test results that they obtained from working with the previous test discs. For this sequence three different masters were recorded after again doing some test masters using 14" video disc master glass coated with the same batch of photoresist using the same coating conditions. These were then used to generate deliverable disc samples that were shipped to Martin Marietta. The three recorded test masters were Log numbers 3944, 3945 and 3946.

The final mastering iteration was completed in November of 1992. For this mastering iteration three masters were recorded - Log numbers 4130, 4131 and 4132. These were planned to be three repeat recordings using the same format definition. This provided three different masters from which to generate stampers for glass formatting. From this Log 4130 was selected to generate the first deliverable samples sent to Martin Marietta. Testing of replicas made from this master indicated the presence of a spot on the disc surface that had missing information. Log 4131 was then selected for pulling stampers and these were used as the source for most of the deliverable discs.

Task 1.2 Stamper Manufacture

For the preparation of the stampers for the TODS program, 3M utilized a proprietary process. Because it is a proprietary process the technical detail describing the process will be kept to a minimum. What is important is the resultant media acceptability of optical discs made from these stampers. The key issues of concern for the stampers themselves were the disc mechanicals and the presence of visual defects in the format area.

For mechanical runout the main issues were the peak to peak radial runout and the eccentricity.

It was possible to take a stamper and measure the amount of its eccentricity and use this as the main response in some of the experiments that were run to try and reduce this eccentricity. Because of the amount of runout tolerance 3M was allotted from the total radial runout tolerance of the system including media, hub and centering spindle, there was a need to keep this to a minimum for the formatted glass itself. For 3M the key issue became the total runout obtained on the assembled hubbed disc, and any attempt to reduce this in each process step offered some advantages.

Also there was some gradual degradation in the quality of the master after pulling a large number of stampers from it. Each stamper might also have some localized damage as a result of the preparation process that would make it unusable for glass formatting. This was determined for each stamper after it was made as most of the serious defects were very visible upon inspection. The good stampers also developed defects during glass formatting, glass replicas would be inspected visually for repeating defects and the stamper would be pulled when appropriate to avoid making multiple glass replicas from defective stampers.

Because of the runout observed in some of the earlier 14" glass formatting runs, several experiments were run in the stamper manufacturing process to try and reduce the runout to an acceptable level. Most of these experiments occurred between the last two mastering iterations and proved to be somewhat successful.

Visual defects were generally introduced as a result of particulates coming between the stamper and the 14" glass surface during the formatting process. Some defects could be removed via special cleaning and some became permanent and resulted in the stamper no longer being usable for glass formatting. This was another area in which several things were done to try and reduce the level of particulates in the vicinity of the formatting equipment. Because of the part sizes involved and the nature of the cleanroom in which the stamper making and glass formatting took place, it was obvious that "perfectly clean" samples would never be obtained. Therefore, the efforts were directed towards reducing these to a minimum. The main things that were done were related to equipment location in the cleanroom, process flow issues and the implementation of better cleanroom techniques. The main defects of concern were those that resulted in beam refraction caused by the lense shape of the defect. This would give rise to refraction of the recorder laser beam and result in tracking loss or hang up of the disc in the disc drive unit during the playback of the disc.

Task 1.3 Glass Formatting

This task utilized a 3M proprietary process as was the case with the preparation of the stampers used in glass formatting. The glass formatting process was essentially the same process that was used by the 3M Sector Lab for their 14" glass optical disc program with some minor modifications that were implemented to correct some of the problems encountered by them in the formatting process. As was the case with the stamper manufacturing process, the main issues of concern in this process step were defects and the format pattern runout.

In the 3M formatting process the glass substrates were coated with two different coating solutions. The first coating was a glass primer that was incorporated because of the

environmental requirements dictated by the program Statement of Work and Product Specification. This was used to insure adequate adhesion of the photopolymer layer to the glass surface. This added another processing step to the glass formatting that resulted in the potential for added yield loss because it provided longer exposure of the glass to the surroundings and an additional opportunity for particulates to settle on the glass. Since the spin coater was located adjacent to the HEPA wall in the cleanroom, the chances of this happening were reduced but it was an issue of concern in the replication process after this priming process step had been added.

As a result it was very easy to prefilter this solution through a 0.2 micron filtration system and eliminate any particulates that might be introduced from the primer solution onto the glass surface during coating. The photopolymer coating immediately followed the primer coating to minimize any additional handling or loading and unloading the glass substrate onto the spincoater. The photopolymer solution used to provide the formatted surface on the glass was a 3M photopolymer that provided the required groove geometry integrity during the environmental testing. This was also applied to the surface of the glass with a spin coating process. The photopolymer solution was also prefiltered through a 0.2 micron filter to remove most of the large particulates and gel particles. The format pattern was replicated into the photopolymer coating using the stamper as the embossing tool and phototcuring to generate the format pattern on the glass surface.

In this formatting process step there were two main issues of concern. The first was the concentricity of the format pattern relative to the center hole of the glass substrates and the second was the presence of contaminants or defects in the specified read/write area of the disc surface. The formatting process could not correct for any eccentricity present in the stamper but any concentricity error introduced as a result of the glass formatting process could be reduced utilizing the orthogonal micrometer adjustments on the tool.

This permitted adjustment in two perpendicular directions that would allow for correction for any error in the stamper format pattern relative to the centering hub on the replication tool. The glass substrates were centered on this centering cone using the chamfer of the center hole cut into the glass by Pilkington, the glass supplier. The concentricity error of the center hole relative to the glass OD was within the specification for the format pattern on the finished disc and was consistent with the concentricity numbers provided by other glass vendors. When initially loading the stamper on the formatting tool, it was usually necessary to generate some concentricity check discs to attain the minimal amount of concentricity error of the format pattern relative to the glass center hole. In the early stages of the program several iterations were required to dial in the proper registration for the glass format pattern. In the latter stages of the program this was reduced to one or two iterations because of the process changes that were implemented. These changes also helped to reduce the variability from disc to disc when replicating multiple copies from a stamper. During the handling process a vacuum wand was used to transport the glass from the spin coater to the replicator. This helped to reduce particulates during this part of the process and to help minimize any fingerprinting on the disc surface.

Because of the issue of particulates and yield losses due to them some changes were made in the process and process flow. The orientation of the equipment relative to the cleanroom HEPA wall was changed to take better advantage of the HEPA wall. Some process changes were also implemented to minimize the chances of particulates settling on either the glass substrates or the stamper itself during idle times when the disc concentricity was being tested on the concentricity tester. During the replication process each substrate was checked visually for any obvious large defects or repeating defects and these were mapped. Several different light sources were used for this process. This was done in tandem with the concentricity check on the disc. For this the disc was placed on the concentricity tester stage with the coated (formatted) side facing down and the microscope was focused through the glass on the very outer OD concentricity test bands to measure the runout of these outermost bands. This was done to minimize any particulates from settling on the format surface during this part of the process. Readings were taken at the various points on the format surface that corresponded to the concentricity adjustment points on the replication tool. Based on this set of readings an adjustment would then be made to correct for the runout of these outer bands and a new replica would then be made and tested. As was mentioned earlier, the intent here was to provide formatted glass substrates with a minimal amount of concentricity error in the format pattern. Any eccentricity present in the stamper would

be present in the glass format pattern. It could not be corrected at this point in the process.

This step was also used to insure that the very outer concentricity test bands were completely intact as you went around the outer edge of the glass. This was a persistent problem in the early program sample preparation but the source of this problem was identified and a change was made in the process to eliminate this problem. This happened to coincide with the time that we were in the process of making glass substrates with the final format definition. In some of the earlier samples these edge defects appeared to correspond to fingerprints on the surface at least in terms of the shape and location on the disc surface. These defects resulted in discontinuities in the outer most test bands at the edge of the disc. Disc handling was initially thought to be the problem. However, subsequent experimentation indicated that this problem had another source and this was remedied after the source was identified.

In general no more than 12 to 16 glass substrates were formatted at any one time as it was found that even with visual inspection during replication that certain defects might slip through undetected. The subsequent coating of the magneto-optical thin film stack would often help to provide enough additional image contrast to permit detection of defects that might otherwise have gone undetected. This also helped to insure consistency of processing for each substrate as it was easier to schedule time on the production thin film coater for a smaller number of individual substrates.

For the deposition of the magneto-optical thin film stack the production thin film coater ended up being the coating system of choice.

<u>THIN FILM COATING:</u>

This was designed to have the capability to duplicate the thin film stack that the production (commercial) coater deposited on the commercial products. The reason for wanting to use the experimental coater at the time was one of scheduling as well as the practicality of using the research tool and not the production coater considering the number of discs to be coated over the duration of the program. In either case some of the issues would be the same. We would need a special carrier to handle the 14" diameter glass substrates since the commercial product produced at the time was a 5 1/4" diameter polycarbonate disc. Secondly the thin film uniformity would have to be addressed for a 14" diameter part with such a large surface area compared to the standard commercial 5 1/4" product.

The intent of this was to insure that there was good circumferential (once around) uniformity of the thin films over the whole 14" diameter area. This was very important at the very OD of the disc as this was the area of highest storage capacity and the uniformity was key to achieve this. This was an uncertain area of need early in the program because there was some ongoing activity in the area of improving the cross and lengthwise pallet media uniformity for this research coating system for the benefit of the commercial product. A result of that would be an improvement in the uniformity of the 14" diameter part and the amount of throughput could be increased as a result of these efforts. One could get almost three complete 5 1/4" discs placed side by side in the same spacing as one 14" diameter glass substrate. If there was any once around variability, then this would result in media recording and playability issues due to the non-uniformity of the optical media. In tandem with this a carrier design was originated for a special carrier that would work with the production coater. It was designed to mesh with the existing disc carrier system so that the carrier would be transparent to the production coater process flow and yet hold the 14" glass substrates.

As the program evolved the situation regarding the two vacuum coaters changed in that the decision was made to have the 14" glass discs coated in the production coater. This was primarily done for two main reasons. First the research coater was being modified and this would have made it very difficult to be able to utilize the initial designed carrier without some major changeovers. Secondly there had been a lot of development work and system optimization on the production coater that indicated that running the 14" glass substrates through the production vacuum coater would give good acceptable media from a uniformity perspective. A special carrier was fabricated that would mesh with the existing transport system on the production coater and this would carry the discs through the system without any changeover to the coater. Upon completion of the coating of all the replicated glass substrates the carrier would be pulled and a normal production carrier put back in its place.

In order to insure the media uniformity witness discs, i.e., discs run through the system on either side of the 14" carrier, were tested and a decision made as to the uniformity and suitability of the magneto optical thin film stack on the glass substrates. This actually turned out to be a good screening tool as several instances were encountered over the duration of the program where some thin film coating problems did arise. When this happened this was recorded in the coating log and these discs were flagged to indicate the problem. This also served to insure that the TODS media had equivalent performance to the commercial product and took advantage of any process improvements that might have evolved during the duration of the TODS program. From a commercial perspective there was always a desire to improve the product performance and consistency and this was an ongoing activity with the vacuum coating system. 3M had a very tight window on several of the key functional parameters for the media and the witness discs were tested against these specifications.

Another benefit of utilizing the production vacuum coater related to the issue of environmental stability of the media. One main issue of concern in generating media is the shelf life of the media. This was especially true for the TODS media which was intended to be used in a ruggedized disc drive environment as was the case with the TODS program. 3M offers a lifetime guarantee for its commercial media and will replace any discs found to be defective with a brand new disc free of charge. The ability to offer this guarantee is in part a result of the development work that had taken place on the manufacturing process for the media. The TODS media would have the added benefit of being manufactured on glass which is a much more stable substrate than the injection molded polycarbonate that is used to make the commercial media. The replication photopolymer has also been shown to be very stable when used in this mode of

application. It had been formulated with some of these issues being key requirements. The other key component in the corrosion resistance and general media stability is the protection coating that is applied over the outer most thin film layer in the optical stack. The commercial protection coating chemistry had been shown to be a qualified material (passed the environmental tests) for this application and also was developed in part with this application as one of the main areas of use.

Since the thin film composition and physical thicknesses of each layer are considered 3M proprietary, no detail will be given here on the construction. As has already been indicated, the intent of the development program was to adapt the commercial process for use in the TODS program and this was successfully accomplished from a thin films perspective. Since there were some differences in the process flow between the commercial products process and the TODS media, there were some differences in the overall cleanliness of the media. This was a given considering the disjointed process flow in the TODS manufacturing process. The commercial operation was all conducted in a straightforward process flow so the handling issues and transportation issues were minimized.

TASK 2.0 PROTECTION COATING

The main activity here was to define the chemistry and the application process for the protection coating for the magneto-optical thin film stack. Since the vacuum deposited magneto-optical thin film stack used to make the TODS media was the same as that used in the commercial product, the initial approach taken was to just utilize the protection coating chemistry that is used in the commercial product. The main issue of concern was the media environmental stability when exposed to 500 hours in the high temperature/humidity environmental chamber (80 degrees Centigrade and 85% Relative Humidity). This is the standard test condition for commercial 3M magneto-optical media.

For the coating equipment the same spin coater was used for this that was used to apply the photopolymer for the glass formatting in replication. The protection coating solution viscosity was such that this was feasible. The only issues became defining the spin speeds and dispense times to give a good coating with the appropriate thickness. The chemistry used is proprietary so it will be only described as a multifunctional acrylate chemistry. The other issue was defining the amount of cure time. Since there were no high volume throughput issues that might have dictated a short cycle time per disc, this never became a factor. Each disc was given a sufficient cure as determined from cure studies conducted with this chemistry on the commercial media.

Accelerated environmental testing of the 3M commercial media (500 and 1000 hour duration tests) indicated that this chemistry provided adequate protection from any high temperature/humidity induced corrosion of the thin film layer. The TODS media also benefited from the fact that the substrate used to make the discs was a chemically tempered glass that was essentially impervious to moisture transfer. This is not true of the polycarbonate injection molded substrates that demonstrate permeability to moisture. For the assembled TODS discs there was also the added benefit of the epoxy bonded hub and the moisture barrier that this provided at the ID of the discs.

TASK 3.0 BONDING

This consisted of two process steps. First the adhesive was applied to each disc half using a special application fixture. In the second step two disc halves were laminated together using a special lamination tool.

Some of the main considerations in the selection process for the adhesive were that it possess good thermal stability, good corrosion resistance, ease of application, no outgassing and no included gels or particulates. At the onset of the program there was a desire to try and be compatible with the Sector Lab 14" glass program that was ongoing at the time. There was an effort at the time to try and have both programs share as much technology as possible to help hold down costs and to try and develop a commercially viable manufacturing process that could be used for both products. Even though the TODS media was not going to be sent into space, there was still a strong feeling that there should be minimal outgassing as this would be the primary concern in a high vacuum environment. Outgassing would present a potential contamination problem in such an environment. In regards to this concern 3M had established an Aerospace Products group that deals specifically with products that are designed to be used in an aerospace environment, so their products would be designed and qualified to meet those requirements.

In regards to the issue of corrosion there would be areas on the disc at the very inner diameter that would not be sealcoated due to the disc clamping mechanism in the spin coater but would be in contact with the adhesive. For this reason it was desired to have a non-corrosive adhesive. Some of the considered materials were ones that had been used in similar applications where they were in contact with thin metallic film layers as is the case in an optical disc application. Here contamination of a corrosive nature would be very detrimental to the functionality of the product. Testing had been conducted for this purpose to help screen some of the potential materials. The issue became one of

evaluating the components in each potential candidate and eliminating ones that would be potential sources of corrosion.

This material was formulated to offer excellent bonding to metal and high energy plastics, provided outstanding temperature and chemical resistance and was a low outgassing adhesive as described in the product literature. This had the benefit of having already been qualified for outgassing in the Sector Lab glass program. It also had been shown to have the added advantage of good damping properties which allowed the discs to meet all of the vibrational requirements as demonstrated by the Sector Lab staff working in conjunction with the vibrational testing personnel.

Having identified the adhesive candidate the next issue became defining the application method. Several approaches were tried early in the program that resulted in some yield losses due primarily to wrinkles introduced in some of these early application attempts. Attempts to precut the adhesive to size and then apply it were very unsuccessful and this approach was dropped early because of the yield issue and general registration problems. In the defined process the adhesive was applied with a pressurized roller and was rolled out from one edge of the disc to the opposite edge using the advancing roller while the disc was held flat on the surface of the platen. The pressure used in the application procedure was 80 psi. Tests with transparent glass reject samples and this adhesive indicated that there was good initial surface wetting which improved with time. The use of the clear glass permitted one to see the wetting patterns of the adhesive. The adhesive was cut into an 18" square sheet, rolled out on the substrate surface and then trimmed after the application to cut out the center hole and trim off the outer edge. A procedure was implemented later in the program in which a way was determined to keep this adhesive very flat prior to the application process (it was supplied in a roll goods form and had some residual curl). This also helped to minimize wrinkles in the adhesive.

For the lamination process a piece of equipment that had been used in a similar application, but for a different product, was modified to accommodate the 14" diameter glass. Basically the fixture consisted of a flat vacuum hold down plate that held one of the two disc halves in place on the flat horizontal surface. This had four registration posts that served to center the disc on the plate. These were spaced at 90 degree intervals. The disc could be loaded so that it had a specific orientation relative to the orientation of the other disc half. The second disc was held in a different fixture that also had four registration posts for centering the disc in the fixture similar to the other half. It also had two separate registration pins that served to align this piece with the other piece as the top piece was being brought into proximity with the other fixed half in the lamination step. This second fixture had two little clamps that gripped the very outer edge of the glass on the chamfer for about an inch circumferentially on opposite edges. These were designed such that they would not interfere with the discs coming together during the assembly as they only gripped the glass chamfer and did not make contact with the information surface of the glass. This second plate was pivoted so that the disc could be mounted in the fixture with it in a vertical position and then pivoted 90 degrees so that the glass substrate was horizontal being held in place with the two gripping clamps. This fixture was attached to a hydraulic cylinder that could be used to bring the one disc half into contact with the other one in a regulated fashion. There were alignment posts 180 degrees apart that were aligned with some bushings on the other fixed half that guided these two halves when mating. This served to keep both disc halves aligned during the assembly process so that there was no side to side shifting or offset during lamination. This also permitted this disc to be clamped such that the areas of highest radial runout would be diametrically opposed to one another so that there would be no imbalance problems in the final assembled disc.

For the actual assembly process one of the disc sides would be placed in the vacuum hold down plate and then the adhesive release liner would be removed. A stainless steel backing plate was then inserted into the pivoting piece and the glass with the stripped liner was placed next to the backing plate and secured at the edge with the two special clamps. The purpose of the backing plate was so that two special retractable bars in the tool could be extended to impart a bow in this disc half. These were two bars on opposite sides of the center hole of the glass that were flush with the backing plate when the backing plate/glass disc sandwich was loaded into the plate and clamped. These fingers were spring loaded so that upon release of the cam shaped lever, they were raised a three eighths inch above the surface of the base plate introducing a bow in the glass (the fingers were aligned along the diameter). This was done to insure that there would be minimal air entrapment when the one side was brought in contact with

the other side. The second side would then be placed on the vacuum hold down plate and the adhesive liner would be removed from this second side. The discs would first make contact along this raised portion of the disc when they first made contact. As the two halves continued to come together, the pressure from the second plate would cause the springs to retract into the base plate permitting the two disc surfaces to make full surface contact. There was also a vacuum system in place so that as the one disc side was in close proximity to the other disc side, a vacuum would be applied while the top clamp was stopped in its downward movement when an airtight seal was made. The applied vacuum would tend to remove any residual air in the system thus helping to eliminate any air entrapment during assembly. Once the desired vacuum level was achieved then the disc would be brought in full contact with the other disc and the bonding would be completed. A high pressure was applied for a very brief period to insure uniform pressure across the full bonded surface of the disc. At this point the laminated disc was removed from the tool and was ready for the hubbing operation.

The problem areas encountered in this process step mainly involved situations where there was a very tight tolerance between the glass ID and the OD of the alignment fingers. In the assembly process several samples were cracked during this final assembly stage by the finger on the movable half hitting the edge of the glass of the bottom fixed half as the two halves were being brought together. This only occurred on a few discs and care was taken to select which disc halves went in which fixture on the tool. Because of the desire to maintain tight tolerances in the alignment of the two disc halves, no modifications were made to the tool to correct this problem. It appeared that only a small fraction of the population of glass substrates as we received them from Pilkington had an inside diameter small enough to cause a problem. Since the centering fingers on the lamination tool were designed to provide a very close tolerance fit with the ID of the glass, any small shift in the final cut size of the center hole would result in a problem at this point in the assembly process. The other issue that seemed to have been introduced in this process step was that there were some small surface scratches introduced into the read surface of the glass on a few samples. There seemed to be a reasonable probability that this occurred in this tool. These tended to be deep scratches and would cause playability problems for the discs in the drive unit.

TASK 7.0 HUBBING

There were two main aspects to the hubbing program. The first issue dealt with the hubbing requirements which included both the materials and the design. In terms of the design the issues were dictated by the centering cone geometry of the TODS Disc Drive

unit as well as the mechanical aspect, i.e., would there be enough mechanical integrity to the design so that it would provide enough strength to provide all of the desired performance requirements. The second issue dealt with the attachment issues and any resultant runout that might be introduced from the attachment process.

HUBBING DESIGN ISSUES:

The design aspect was one that was addressed through a lot of interaction between 3M and Martin Marietta, especially during both the Preliminary Design Review and the Critical Design Review. Machinability, thermal expansion, anti-corrosive properties and mechanical stability were important considerations in the determination of the final hub specification. In the early phase of the program Wayne Hector initiated some finite element analysis modeling to simulate a thermally stressed assembled disc construction to identify any possible stress points. This would eliminate a lot of tooling costs for the manufacture of these various prototypes. This proved to be a valuable technique in arriving at a design that was put to print and machined for some actual bonding trials with glass. The other part of the design issue was the specification for the center hole size of the glass as we receive it from the Pilkington vendor. This too would have an impact on the amount of surface area available for chemical bonding and/or the use of mechanical fasteners, i.e., screws. In terms of the material of choice the decision was made to go to a 430 Stainless Steel. This was done for several reasons. It is used in other optical discs, has good corrosion resistance, good hardness, approximates the thermal coefficient of expansion of the glass and is readily available which should reduce the cost aspect. In general there are some tradeoffs between some of the thermal and corrosion resistance properties of these materials. The reason for the choice of the #430 was that it seemed to have the optimum combination of properties for this purpose. The design that was arrived at also incorporated 6 screws (2/56 x 1/8") that would serve as mechanical fasteners to enhance the integrity of the assembled disc construction. Factored into the hub design was a reasonable amount of clearance between the glass ID and the hub OD so that a limited amount of concentricity/eccentricity error from the formatting process could be compensated for in the hubbing process. The holes were aligned during the attachment of the second side hub prior to fixing the hub in position to permit the epoxy adhesive to cure with the hub holes in proper alignment. The final assembly step was to actually bond the screws in place using the same epoxy adhesive used to bond each individual hub to the glass.

HUBBING ATTACHMENT:

A special tool was utilized for the disc hubbing process. It was a tool that had been used in another program for a similar application but that was modified to accept the TODS hubs and glass substrates. Essentially the tool had a movable base plate that permitted adjustment in two perpendicular directions for purposes of minimizing the runout of the format pattern relative to the referenced chamfer surface on the center hole of the attached hub. The tool had a microscope and attached camera that would focus on the outermost concentricity test bands that were part of the format pattern as specified in the format definition. There was a special centering adapter that slid on the centering post of the tool that permitted the disc to be roughly centered on this relative to the ID of the glass for its initial placement. The final concentricity adjustment was accomplished through the tool. A microscope was focused on these tracks and the disc was rotated manually and readings were taken at the 90 degree intervals that corresponded to the centering cone adjustment points. These readings were then used to adjust the base plate holding the glass using two orthogonal micrometers so that the final amount of runout of the OD test bands relative to the hub reference surface was minimized through an iterative adjustment process. The vacuum hold down plate could be moved relative to the centering cone for the hub. The centering post had a chamfer on the centering cone that matched the taper geometry of the centering cone of the actual disc drive unit. The hub to be bonded was then placed on this centering cone that allowed it to be centered on the reference chamfer that would be utilized in the TODS disc drive unit. The centering cone assembly of the hubbing tool also had the capability to float vertically so that the hub could be placed on the base plate of the centering tool and then have the chamfered centering post be gradually raised to have the hub center itself on the chamfer of the centering hub. This resulted in minimal tilt of the hub so that it did not shift when being brought into contact with the glass surface. The floating centering cone assembly was on a threaded shaft so that it could gradually be raised to bring the hub into firm contact with the glass squeezing out the epoxy adhesive into the desired thickness for maximum bonding. This was then held in place while the epoxy cured.

In the course of the disc hubbing process evolution several types of problems were encountered. The first of these was a problem in which there was some shifting of the hub after the initial alignment/attachment and during the curing process. This may have been due to removing the disc from the hubbing tool prior to allowing sufficient cure time for the adhesive. Another possible reason was that in the early sample preparation, the amount of dispensed adhesive was too large and there was some residual adhesive resting in the disc clamping area that had to be removed so that the disc could be

clamped and played in the actual disc drive unit. The removal process may have generated some stress on the hub resulting in some shifting. There were some process changes implemented to try and address these issues. First for the side A hubbing process the bonded hub was permitted to cure without any removal from the hubbing tool for at least 12 hours. There may have been some additional curing of the first hubbed side after it was removed from the hubbing tool and before any side B hub registration and bonding was attempted. This was usually the case when several samples were being assembled at the same time. This would tend to give more complete cure and minimize any tendency for the hub to shift during any subsequent handling processes. The other issue was addressed by trying to automate the dispensing process as much as possible so that just the right amount of adhesive was dispensed. This was determined by use of a test sample in which a hub was bonded to a clear piece of glass. The adhesive was dispensed using the dispensing tool and then the hub was centered and attached using the normal procedures. The clear glass then permitted one to see if there was just the right amount of adhesive dispensed or if it needed to be adjusted. This would then serve to define the dispensing parameters for actual disc assembly.

The problems encountered in the attachment of the second side hub were primarily due to shifting of the second side hub when the centering hub was being brought into contact with the glass surface. This problem was minimal but it did occur. For most of the final deliverable discs if this occurred the disc was disassembled and both the hub and the glass surfaces were recleaned and then the disc was reassembled. This was possible because of the set time for the epoxy adhesive and its good solubility in ketone solvents. The other problem that occurred on occasion was that in attaching the screws that were used to align the holes in both hub halves, there might occasionally be burrs in the threaded section of the hub holes, and this could cause the hub to shift when the screws were screwed into the holes. To address this problem the hub and screws were pretested without any adhesive to make sure that they screwed in freely with no binding of the screws in the holes. Care was also taken to remove any excess adhesive in the area of the chamfer or bore in the hub prior to its setting up and curing as this could result in a runout error when placed on a test fixture or the disc drive unit itself.

TASK 5.0 PRODUCT MANUFACTURE

Because of some of the unique characteristics of glass and some of the phenomenon that was observed during the course of conducting the TODS contract, some general

comments will be made about the subject of optical glass in general as this might help to further the understanding of some of these issues.

From a chemical perspective there are several compositions that are used in the manufacture of bulk glass that are ultimately used in the preparation of sheet substrates for optical discs amongst other products. There are some variations in these from vendor to vendor as most of these generate their own starting bulk material which is then subject to additional processing to form it into the various end products. The main compositional differences depend on the glass vendor. Asahi makes a synthetic quartz glass substrate that has an extremely low expansion coefficient, high light transmission in the ultraviolet range and excellent chemical endurance. These requirements can determine the composition of choice as the final product may have unique requirements for the values of coefficient of expansion, chemical durability, light transmission, refractive index and the softening point. From the standpoint of an optical disc application there are unique requirements for the refractive index, coefficient of expansion, light transmission and the chemical durability, and the chosen compositions and processing are designed to meet those requirements.

In the optical glass substrate area that most glass vendors dealt with on this contract, there were two main glass compositions used to fabricate glass disc substrates. The first of these was the soda lime family of glasses and the second of these was the alumino-silicate family of glass. Some general comments should be made regarding the differences between these two families of glasses.

In general glass is a ceramic material consisting of a uniformly dispersed mixture of silica (sand), soda ash and lime. The sand refers to the SiO_2 component, the soda ash refers to the sodium carbonate Na_2CO_3 and lime refers to calcium oxide CaO. In general the material is characterized by the level of the silica component as the main ingredient and then the levels of sodium dioxide and other metallic oxides are specified as percentages. Soda lime glass refers to a glass with a relatively high percentage of sodium dioxide and a relatively low level of aluminum oxide. The main constituent is SiO_2 with oxides making up the rest. This is in comparison to the alumino-silicate glass which generally has a lower level of the SiO_2 and the sodium oxide but with a higher level of the Al_2O_3 component, thus the reason for the alumino-silicate designation. Corning, one of the vendors contacted in the proposal writing and early research phase of the program, favored the alumino-silicate family of glasses for their optical disc substrates. They have published information on their 0313 alumino-silicate glasses and have found that there is less alkali migration due to the compositional difference

resulting in less media weathering, higher media performance and longer media lifetimes. They primarily offered this glass in smaller sizes (5 1/4") and were not able to provide or quote for 14" diameter sizes so they were not actively pursued as part of the development program. They do provide a lot of glass for this type of application and have a lot of expertise in this area due to the nature of their core businesses in the glass and ceramics areas.

Asahi and Hoya, two other large Japanese glass manufacturers, offer both types of glass for optical disc applications. Both of their product bulletins specify substrates up to 300 mm (12") in diameter as standard products so the 14" size was not a standard one for them and was not produced commercially for any other customers. They manufacture substrates for both optical and magnetic applications and for the optical area they made substrates for both the mastering process (mastering glass blanks) as well as for the discs themselves. In general their physical specifications for the various sizes and the tolerances were not a great deal different from the other vendors that 3M dealt with for the standard sized products.

On the European side the main players dealt with were Glaverbel and Pilkington. Pilkington had been a primary supplier to several optical disc companies and seemed to be the most willing to work with us in providing substrates that would meet our requirements. The larger size simply meant that they would adjust their cutting tool to cut blanks with the larger OD and also adapt their ID cutting tool to provide the required ID. Pilkington has conducted a number of studies in the area of optical disc applications for their glass substrate products and met with us several times when the program was being started. Their main focus has been in the area of soda lime glass as this was their material of choice for optical substrates. Some of the main differences between optical substrates manufactured out of soda lime glass versus alumino-silicate can best be summarized in the following table which lists a number of typical properties:

Property	Soda Lime Glass	Alumino-silicate Glass
Hardened Layer	15-25 microns	125 microns
Compressive Stress	48 Kg/mm^2	198 Kg/mm^2
Surface Hardness	550 Kg/mm^2	650 Kg/mm^2

As can be seen the alumino-silicate glass typically has a much thicker hardened layer compared to the soda lime glass. Some of the results of these differences are that the hardened alumino-silicate glass can have a greater tolerance for surface scratches as

there is a greater compressive force to overcome in order for the crack to propagate resulting in fracture of the glass. There is also greater resistance to surface penetration from an indentation probe. This can be varied somewhat by the process but the relative thicknesses of each type of glass are representative of what might be expected. For the people that had worked in the Sector Lab on their program, their experience was that in their early dealings with the alumino-silicate glass that if there was any failure due to brittle fracture, it was catastrophic in the case of the alumino-silicate. This was generally brought about when there was a surface crack at one of the edges (either ID or OD) of the glass. For most of their program and for all of the TODS program all of the work was done on soda lime glass as that was the material offered by Pilkington who was the main glass source of supply of the 14" glass substrates for both programs.

Some general comments should be made about the haze issue that became a problem with the TODS program. The glass substrates as shipped from Pilkington are placed in a 20 disc carrier that was fabricated from a special grade of polyester resin. This was chosen so that there would be no transfer of any materials (additives) from the shipping container itself to the glass surface. This shipping container was banded to keep it secure and this was then packaged in a foil liner to seal the inner polyester container from any external environmental influences. During the course of the contract it was found that the containers of glass as received from Pilkington, if not opened within the first 9 months for use, were found to have developed a layer of haze on the surface of the glass. This was observed visually when the containers were ultimately opened after this period of 9 months or longer. This became a factor for the TODS program due to some early program delays that resulted in some inactivity, and not having a need to replicate any glass for a period of time. There were two main problems due to the presence of this haze. The first was an optical one in that you could visually see the haze on the surface of the glass using an inspection lamp at a low incident angle and this scattered the light. The second issue was one of non-wetting due to the presence of the deposit on the surface of the glass. This resulted in severe non-wetting of the glass when coated with the replication photopolymer during the glass formatting process. The photopolymer solution would literally pull back away from the edge of the glass resulting in no format being replicated in that area as well as a loss of adhesion of the coating on the glass. Attempts to eliminate this haze using a high pressure water jet cleaning device that we had in house did result in haze removal, but did not solve the non-wetting problem. At one point in the program a container of glass was shipped back to Pilkington for the purposes of doing a recleaning and this was successful as the glass upon return to 3M did not exhibit the non-wetting phenomena. This was not a practical solution due to the costs involved in shipping the glass back to the UK and the resultant

shipment from Pilkington back to 3M. The ultimate answer to this problem was to have the glass prepared and shipped on a "Just In Time" basis so that the glass was always used prior to the onset of the haze on the surface of the glass. The other complicating factor in this was the yield issue in that for each scheduled deliverable requirement, it was not known how many pieces of glass would be required to make the required samples.

TASK 4.0 TEST TECHNIQUES

This is a topic that has been referenced in other sections of this report. The main issues of concern in this area were threefold: Mechanical Testing, Dynamic Testing and Environmental Testing.

In the mechanical testing area the main issues of concern during the program were the radial runout of the format pattern both for a single sided disc as well as for a hubbed, laminated two sided disc and the flatness or droop of the disc. 3M had a special tester in house (Camarillo Tester) that was designed and built for purposes of doing mechanical testing and some rudimentary tracking testing on some of their earlier media. This was capable of being adapted for the TODS media testing through the fabrication of some special test clamps for the test fixture that could accommodate both the unhubbed and hubbed samples. These could then be used to test the special outer concentricity test bands that were included for 3M's testing as part of the recorded format pattern. 3M was allocated a certain amount of radial runout due to other contributing factors in the disc drive unit that could result in additional runout. Runout limits were allocated for each interface or segment of the system and the sum total of all of these contributing elements had to be less than the disc drive unit designed to handle or correct for. From 3M's perspective there were a couple of contributing factors to the sum total radial runout. The first of these was the amount of runout that was contained in the stamper as pulled from the initial recorded glass master. Once this was frozen in as part of the stamper there was no way to reduce this. It could in the best scenario be held the same during the glass replication process. In general, however, the glass formatting was another area where additional concentricity/eccentricity error was introduced. During the replication process itself there was a possibility that the registration of the stamper relative to the disc centered on the registration cone on the replicator would shift. This initially was a big problem and it varied considerably from disc to disc due to variability in the way the disc was centering itself on the replicator platen through the use of the centering cone. This became an early source of yield loss because of the excess radial runout that was obtained on the discs. This was primarily due to the centering

mechanism used on the replication tool itself being inconsistent due to the mechanism with which the disc was secured in place on the replicator platen after centering on the cone. In lowering the disc/centering cone plunger there was a certain amount of vibration introduced in the glass as it made contact with the replicator platen. If the vacuum hold down trigger was not activated properly, then there would be some slight shifting of the glass before the vacuum became sufficient to hold the glass substrate in place. In the latter stages of the program a process change was implemented that helped to remedy this problem.

For testing replicated discs in process a special test fixture was used that was located right next to the replicator. This had a centering cone with a duplicate chamfer to the centering cone that was used on the replicator so that the glass could be centered on it in an analogous fashion to the way the glass centered on the replicator centering cone. The peak to peak radial runout was measured using a microscope that had a calibrated vernier scale with which the actual runout of the outer concentricity test bands could be measured to obtain peak to peak runout. This information could be correlated with the corresponding position on the replication tool. Adjustments were made to correct for any concentricity error using micrometers attached to the moving centering cone. In the early phases of the program this was more of a hit or miss approach as there was a certain amount of variability in the way the glass substrate would center itself when lowered onto the replicator. This was primarily due to the way in which the disc was lowered on to the replicator after it was allowed to center itself on the chamfer of the centering cone. This was designed to have the same chamfer as the centering cone in the TODS Drive Unit itself to try and minimize the runout as referenced from this chamfer surface. Subsequent adjustments and modifications were made to the replicator tool that seemed to eliminate a large amount of the eccentricity variability that had been taking place with the previous setup. It now became possible to dial in the concentricity when first starting to replicate in one of two replicas. The concentricity tester used at this stage in the process seemed to correlate well with the subsequent testing of the discs after thin film coating, sealcoating and adhesive application. There was a certain amount of eccentricity inherent in the stamper replicated glass substrates, but for certain stampers and discs replicated from those stampers, the actual amount of peak to peak runout was 12 microns or less. This was in comparison to the runouts of 40 to 50 microns that were much more typical early in the formatting process. This improvement was in part due to some process development activities that were conducted in the middle of the program. Improvement at this phase in the process permitted a little more latitude in the subsequent hubbing process as this was an issue for some of the earlier hubbed samples due to some slippage possibly during the curing

process. However, this was an area that was subjected to some process changes driven by these slippage issues. The end result of this was that there seemed to be more consistency in the hubbing operation. In the hubbing operation the hub was centered relative to the outer most concentricity test bands and in the hubbing tool centering could be done even if there were discontinuities in the outer most test band. This was used to try and compensate for any concentricity error of the format pattern relative to the center hole of the glass. A certain amount of concentricity error could be compensated for in the hub attachment process. It was the intent, however, in the glass formatting process to try and center the format pattern relative to the glass inside diameter chamfer to allow as much latitude as possible in the hubbing operation. This also facilitated the disc lamination process in that there was minimal side to side concentricity error as a result of the efforts taken in the glass formatting process.

For the dynamic media testing one of the key tests became the real time testing that all of the witness discs were subject to immediately following the thin film testing. This gave immediate response and feedback as regards to the acceptability of the deposited thin film stack. This gave a measure of both the cross pallet and up and down pallet variations that might have occurred. The variation from disc to disc was in most cases well within the requirements for the 14" product. This was one of the advantages of coating the 14" replicated glass substrates in the production coater as it benefited from all of the in process control instrumentation as well as the in line process testing for determining any potential problems in any of the layers in the optical stack. This also became important because of all of the problems that had taken place for a good deal of the program in being able to have a complete outer concentricity test band with which to test the discs on the specially adapted 3M dynamic test system. For most of the early discs this band had some discontinuities in it that precluded any testing on the special TODS test fixture that had been built for this purpose. Since media uniformity at the very OD of the disc was the main area of concern, this ability to be able to rely on the in process testing numbers became very important. There was an ongoing activity to improve the uniformity of the commercial media so the TODS discs benefited from this development.

In the area of environmental stability the TODS media would be subjected to operational conditions that the commercial media was not designed to meet. The media had to perform in a ruggedized design environment. This not only included extremes in temperature and humidity but also in terms of some of the vibrational requirements that it might see in its operational mode. The standard 3M environmental test involves prolonged exposure to a high temperature/humidity test at 80 degrees Centigrade and

85% Relative Humidity. The main response for this test is the BER value for the media. 3M has a minimum standard that must be met by media subjected to this condition for 1000 hours. In the 3M test the media is first tested in a disc drive unit for the BER numbers using a predefined test procedure. The media is then put into the chamber for a 500 hour interval and then pulled out and retested on the same disc drive using the same test sequence. This testing has been the basis for the 3M Lifetime Product warranty that guarantees that 3M will replace free of charge the customer's disc if it is found to be defective. For the TODS media the same test was run in terms of the temperature and humidity conditions. The main difference was that instead of running a BER test on the media, it was subject to a visual inspection to check for the presence of corrosion in the thin film stack. This was a test method used for other experimental programs when the appropriate disc drives were not available for actually drive testing the media. Experience had shown that this, although not being a highly quantitative test method, gave a very good indicator of what might be expected of the media subjected to this high temperature/humidity test. Because of the ongoing activity at Martin Marietta with their own in house testing on the disc drive unit and the inability to get test feedback on discs for purposes of environmental testing, the qualitative approach was used to study the impact of the environmental tests. The target was 500 hours at 80° Centigrade and 85% Relative Humidity. The discs were held on a special holder and were supported at the ID chamfer of the stainless steel hub using a Teflon support rod. This exposed both the ID and the OD of the hubbed laminated disc to the environmental test condition to maximize the possible exposure of the disc to any potential corrosion mechanisms. Since the sealcoating is the same as that used in the commercial product, then it was expected that the same stability observed in the commercial media would be obtained here. This was found to be the case. Another issue working in TODS favor was that there was no push to get large quantities of discs through the system so that there was plenty of time available to do a complete cure of the sealcoated disc samples. This has been the main issue with environmental failure in the past. It has been generally been traceable back to sealcoating (protection coating) issues.

In the area of high temperature and low temperature testing, as well as thermal shocking, the main issue of concern has been one of disc integrity, i.e., will the disc delaminate or will the hubs shift or fail. Again here the response has been a combination of visual observations as well as testing of the radial runout on discs centered via the hub. The tests that were run were as follows:

Low Temperature Test: 72 Hours at -40°C

High Temperature Test: 72 Hours at 77°C

For these tests the same set of discs was used to conduct all of these tests. This was done to simulate what actually might happen to any given set of discs. During the course of using a disc set in a non-operational/operational mode they might be subject to the whole spectrum of these test conditions, so that there might possibly be a cumulative effect of being exposed to the various test conditions. Again here the disc construction demonstrated good structural integrity as there was no failure as a result of subjecting sets of discs to the above test conditions. This was in part due to the selection of the adhesive for disc lamination as well as the epoxy/primer chosen for the hub attachment. These were both designed for use in extreme temperature conditions where other materials might fail. Work done on the preceding 14" Optical Disc program in the Sector Lab had also shown the laminating adhesive to possess good stability and excellent damping characteristics as shown in their studies in which they subjected a disc laminated with the acrylate based adhesive to a variety of vibrational testing modes which the disc passed with no problems.

TODS PROGRAM SUMMARY

The TODS optical disc media program was designed to adapt existing commercial processes used to manufacture 5 1/4" media to prepare magneto-optical 14" glass based optical disc media. The main difference was that a 14" diameter glass substrate was used instead of an injection molded polycarbonate substrate. The other key differences were that the TODS media was intended to be utilized in a ruggedized drive environment which meant that it would be used in an Air Force aircraft, would be exposed to temperature extremes, humidity extremes and subject to various vibrational modes as a result of the maneuvers that the plane would experience in a normal operational mode. This necessitated a lot of both materials and process development activities to adapt the existing technology to produce the 14" glass based media with all of its unique requirements.

In its early stages the TODS program activity was coordinated very closely with the Sector Lab personnel who were working on a similar program having a lot of similarities - 14" glass substrates, photopolymer replication, designed to operate in a ruggedized environment (space station) and intended to be based on the same media technology (magneto-optical) as was the TODS program. Part of the intent of the TODS development process was to design a commercially manufacturable process that could be used in the event of a need for a large number of discs for future programs with either customer. For the most part this objective was followed in the establishment of the manufacturing process. The main areas of concern, where it was not followed, were

areas that were dictated by other needs or concerns. These issues were primarily ones of relating to the process flow. It became necessary to share some resources with the Sector Lab which meant that some process steps were carried out here in 3M Vadnais Heights and some were conducted in the Sector Lab cleanroom at the 3M Center utilizing their spin coating and replication equipment. The end result of this disjointed process flow was one in which particulates and general cleanliness became issues. There were special containers used to transport the discs in a sealed environment but the added handling that was involved in transporting the discs back and forth only worked against the goal of having "clean" discs. The other issue working against this goal was the manually intensive way in which the formatting was accomplished. This ideally should be a very automated process in which human involvement is kept to a minimum as this is typically the main source of particulates. However, it was not in the scope of this program to provide a very automated process to produce the discs so the resultant discs had more in the way of particulates and defects than might otherwise have been the case. Most of these deficiencies were acknowledged at the beginning of the program and the underlying intent was to conduct the program on a "Best Effort Basis" and deal with the issues as they developed. Because of the size of the media it was necessary to build or adapt a lot of special tooling for the various process step as well as to adapt existing test fixturing to be able to test the TODS samples. There was a scheduling issue in getting the formatted glass substrates coated in the production thin film coater once the decision was made to coat the TODS media in this system. This actually worked out to be a good decision, however, as the production coater had been fine tuned to the point that the media uniformity on a 14" part was significantly improved over the initial runs through the experimental research coater (PCX). The special carrier that was fabricated to carry the substrates through the production coating system was made such that it would mesh completely with the in process control system that was incorporated into the coater. As a result, other than the special loading and unloading that was required for each TODS coating run and the insertion of the carrier into the system, the coating operation was not varied in any way from the coating of the production "witness" discs that were coated immediately before and after the TODS carrier. This meant that the witness discs would truly reflect the media dynamic performance that could be expected of the 14" disc samples. This meant minimal disruption to the system.

Some of the other issues that had to be dealt with primarily involved ongoing process improvement activities that addressed individual problems as they arose. If this program were to have been continued in the next phase, which had been requested of 3M, the

main recommendations for changes that should be implemented to try and improve the overall yield and process efficiency would be the following:

1. Establish a dedicated facility for the purpose of producing the TODS media. This would address the process flow issues that occurred in the initial TODS program that resulted in additional yield losses due to the added handling of the discs.

2. Allocate funding for a new replicator design that would eliminate a lot of the human activity and manual handling of the substrates that also resulted in some yield losses. A Japanese company manufactures a system for doing photopolymer replication of both glass and plastic substrates that utilizes a robot in conjunction with a special cartridge system that would substantially automate this key part of the process. The system presented to 3M permitted photopolymer formatting for substrates up to 200 mm in diameter. However, this could probably be adapted to make larger format sizes, i.e. 14". The key factor in making clean substrates is to try and minimize the human element. The costs of this approach would have to be weighed against the benefits and pro rated over the number of required discs in any contract. Given sufficient volume this would probably have a reasonable payback in terms of yield improvement.

3. Consider a smaller form factor for the media. In establishing the TODS program it became obvious that there was a lot of automated equipment that could handle up to 12" diameter substrates that was not available for the 14" size. This would become important if the volumes increased significantly. The other issue here is the packing density projections for commercial media and the adaptation of these technology changes to the larger format sizes. This would allow for the same storage capacity in a smaller size media and be more compatible with some of the process equipment that is commercially available.

3M's desire to not submit any new proposals for additional media for this technology was based primarily on the fact that this was very much a niche market and that 3M's position is to try and commit to contracts that have long term commercial opportunities. This was not the case with TODS. For every process step there was a special piece of equipment that was not compatible with the commercial process. This resulted in added costs and added headaches due to all of the special handling involved.

In general based on the feedback and communications with Martin Marietta during the final testing phase, they were very pleased with the media. Sparing sectors which was not in the original software plan became necessary due to the presence of defects on the disc surface in the established read/write area. This was the case due to the process flow involved in the disc manufacture. However, the overall BER numbers were very acceptable to them and in general the media performance was found to be acceptable to them.

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